

# **CONTRACTOR REPORT**

SAND99-1477

Unlimited Release

Printed June 1999

## **Investigation of Synergy Between Electrochemical Capacitors, Flywheels, and Batteries in Hybrid Energy Storage for PV Systems**

John Wohlgemuth  
Solarex  
630 Solarex Court  
Frederick, MD 21703

Dr. John Miller  
JME, Inc.  
17210 Parkland Drive  
Shaker Heights, OH 44120

Lewis B. Sibley  
Tribology Systems, Inc.  
239K Madison Avenue  
Worminster, PA 18974

Prepared by  
Sandia National Laboratories  
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,  
a Lockheed Martin Company, for the United States Department of  
Energy under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination is unlimited.



**Sandia National Laboratories**

Issued by Sandia National Laboratories, operated for the United States  
Department of Energy by Sandia Corporation.

**NOTICE:** This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831

Prices available from (703) 605-6000  
Web site: <http://www.ntis.gov/ordering.htm>

Available to the public from  
National Technical Information Service  
U.S. Department of Commerce  
5285 Port Royal Rd  
Springfield, VA 22161

NTIS price codes  
Printed copy: A03  
Microfiche copy: A05



## **Investigation of Synergy between Electrochemical Capacitors, Flywheels, and Batteries in Hybrid Energy Storage for PV Systems**

John Wohlgemuth  
Solarex  
630 Solarex Court  
Frederick, MD 21703

Dr. John Miller  
JME, Inc.  
17210 Parkland Drive  
Shaker Heights, OH 44120

Lewis B. Sibley  
Tribology Systems, Inc.  
239K Madison Avenue  
Worminster, PA 18974

### **Abstract**

This report describes the results of a study that investigated the synergy between electrochemical capacitors (ECs) and flywheels, in combination with each other and with batteries, as energy storage subsystems in photovoltaic (PV) systems. EC and flywheel technologies are described and the potential advantages and disadvantages of each in PV energy storage subsystems are discussed. Seven applications for PV energy storage subsystems are described along with the potential market for each of these applications. A spreadsheet model, which used the net present value method, was used to analyze and compare the costs over time of various system configurations based on flywheel models. It appears that a synergistic relationship exists between ECs and flywheels. Further investigation is recommended to quantify the performance and economic tradeoffs of this synergy and its effect on overall system costs.

Intentionally left blank.

## **Acknowledgments**

The authors would like to thank the Energy Storage Systems Program at Sandia National Laboratories and the Department of Energy's Office of Power Technologies for sponsoring this work.

Intentionally left blank.

# Contents

1. Preface .....	1
2. Introduction .....	3
3. Storage Technologies.....	5
3.1. Flywheels .....	5
3.1.1. Advantages in PV Systems.....	7
3.1.1.1. Compatibility with Remote Sites .....	7
3.1.1.2. Longevity .....	7
3.1.1.3. Lack of Maintenance .....	8
3.1.1.4. Insensitivity to Deep Cycling.....	9
3.1.1.5. Surge Capability .....	9
3.1.1.6. Tolerance of Ambient Temperature Extremes.....	10
3.1.1.7. Lack of Environmental Impact .....	10
3.1.2. Disadvantages in PV Systems.....	11
3.1.2.1. Cost.....	11
3.1.2.2. Reliability.....	13
3.1.2.3. Surge Capability.....	13
3.2. Electrochemical Capacitors.....	13
3.2.1. Advantages in PV Systems.....	15
3.2.1.1. Lack of Maintenance .....	15
3.2.1.2. Longevity .....	15
3.2.1.3. Environmentally Benign.....	15
3.2.1.4. High Discharge Rate Capability.....	15
3.2.2. Disadvantages in PV Systems.....	15
3.2.2.1. Self-discharge Rate.....	15
3.2.2.2. Cost.....	16
3.2.2.3. Output Voltage Control .....	17
3.3. Capacitor/Flywheel/Battery Combinations .....	17
3.3.1. Flywheel/EC Systems.....	19
3.3.2. Battery/EC Systems.....	19
4. Applications .....	21
4.1. Instrumentation/Highway Call Box .....	22
4.2. Grid-independent Residential.....	22
4.3. Telecommunications .....	22
4.4. Grid-connected Residential .....	22
4.5. Electric Vehicle Charging Station .....	23
4.6. Grid-connected Commercial .....	23
4.7. T&D Support.....	23
5. Market Analysis.....	25
5.1. Net Present Value Analysis.....	25
5.2. Potential Markets .....	25
5.2.1. Instrumentation/Highway Call Box .....	26
5.2.2. Grid-independent Residential .....	27
5.2.3. Telecommunications .....	27
5.2.4. Grid-connected Residential.....	28
5.2.5. EV Charging Stations.....	28

5.2.6. Grid-connected Commercial.....	29
5.2.7. T&D Support .....	29
5.3. Market Scale .....	30
6. Conclusions .....	33
6.1. Flywheel Status .....	33
6.2. Development of Low-cost ECs .....	33
6.3. Flywheel/Capacitor Synergy .....	33
7. Appendix A: Capacitor Manufacturers and Technologies.....	35
8. Appendix B: Vendor Information .....	39
9. Appendix C: Net Present Value Analysis (Example).....	41

## Figures

Figure 1. TSI Bellcore flywheel.....	6
Figure 2. Ragone plot for P/E ratios of current flywheels.....	9
Figure 3. U.S. power quality equipment market segments.* .....	31

## Tables

Table 1. TSI Flywheel Production and Development Cost Estimates .....	12
Table 2. Characteristics of Flywheel Rotor Materials.....	18
Table 3. Application Categories for PV Systems.....	21
Table 4. Flywheel Market Projections Based on TSI Flywheels .....	30
Table 5. Projected 5-year Annual Flywheel Market Size Based on TSI Flywheels .....	30
Table 6. Comparison of Near-term and 5-year EC Costs Based on TSI Flywheels .....	31

## **Acronyms and Abbreviations**

ATTB	Advanced Technology Transit Bus
CMOS	complementary metal-oxide semiconductor
DARPA	Defense Advanced Research Projects Agency
DOE	U.S. Department of Energy
EC	electrochemical capacitor
EPRI	Electric Power Research Institute
EV	electric vehicle
HEB	hybrid electric buses
HEV	hybrid electric vehicle
NASA	National Aeronautics and Space Administration
NPV	net present value
NREL	National Renewable Energy Laboratory
PNGV	Partnership for a New Generation of Electric Vehicles
PV	photovoltaics
RFQ	request for quote
T&D	transmission and distribution
TSI	Tribology Systems, Inc.
UPS	uninterruptible power supply
VRLA	valve-regulated lead-acid

Intentionally left blank.

## **1. Preface**

The focus of this study was an investigation of the synergy between electrochemical capacitors (ECs) and flywheels in combination with each other and with batteries as energy storage subsystems in photovoltaic (PV) systems. The focus was driven partly by economics; the high cost of available ECs precluded their use as direct replacements for lead-acid batteries in virtually all applications that require moderate to high energy densities. Thus, this study focused on how the unique capabilities of ECs (fast response, longevity, tolerance of temperature extremes, etc.) could justify their use in combination with other storage media. During the course of the study an emerging EC technology was identified that may be available at a cost low enough to challenge the initial high cost assumptions for ECs. If the new technology delivers on its potential, both for energy storage and cost, ECs could become a viable replacement for lead-acid batteries in certain applications.

Intentionally left blank.

## 2. Introduction

Sandia request for quote (RFQ) BD-0005 was directed at the first phase of a possible multiphase research project to identify user needs and application requirements for improved integration of renewable energy generation technologies with energy storage systems. In response to this RFQ, a team headed by Solarex proposed to investigate the feasibility and potential of using ECs and flywheels, either singly or in combination, as energy storage media in PV power systems.

Three-quarters of the PV systems deployed today use batteries as storage, despite the fact that in many of these systems batteries have known drawbacks, most notably:

- The poor life span match between batteries and PV. In a typical system, the battery bank is replaced three or four times in the first 20 years of the PV array's life. Replacement is expensive, not just in purchase price, but in transportation and installation.
- The incompatibility of remote sites (common for PV systems) and batteries' maintenance requirements and weight.
- Their comparatively poor (approximately 50%-70%) energy efficiency in a PV system.
- The safety and environmental considerations, detailed later in this report.

These drawbacks illustrate the technology "gap" (in terms of the RFQ), where battery systems do not truly meet the needs of existing applications and, additionally, have not been broadly adopted by emerging applications such as standby power and transmission and distribution (T&D) support stations. This study looks at those systems as potential applications for new storage systems, and investigates the possibility of these new media broadening the applicability of PV power to applications not presently served.

Team member JME provided information on ECs and identified ESMA (a Russian company) as a possible source of low-cost "traction" capacitors. Team member Tribology Systems, Inc. (TSI) provided information on flywheels and TSI flywheels were used as representative models in this study. Preliminary analysis suggests a synergy between ECs and flywheels. ECs respond very quickly to changes in input and load, which complements the low-loss storage capability of the flywheel. Both are virtually maintenance free, potentially expanding PV's already significant penetration of the remote power market. Further, both are environmentally benign.

Intentionally left blank.

### **3. Storage Technologies**

This section describes the energy storage technologies investigated with respect to their general characteristics as storage media in PV systems.

#### **3.1. Flywheels**

Flywheel development has been directed primarily at two areas: vehicular propulsion and storage as part of an electrical system. Flywheels are particularly compatible with electric and hybrid electric vehicles (EVs and HEVs), where they can serve as a primary storage medium or as a surge power source enabling enhanced vehicle acceleration and battery life. They are also compatible with the regenerative braking systems common to these vehicles. They have been investigated for vehicular purposes since the late 1960s, when Oerlikon operated several buses in South Africa utilizing flywheels as primary propulsion.

The technology advanced significantly with the development of carbon composite materials for the rotor. Replacing steel, these materials provide more strength with less weight, and greatly reduce the risks previously associated with rotor disintegration. Various prototypes that employ composite rotors are presently in use, including one in a BMW demonstration vehicle. Another prototype is to be installed in an EV presently being tested at Hanscom Air Force Base in Massachusetts.

Flywheels are also being developed or are in prototype demonstration for several modes of use in electric systems.

- A flywheel manufactured by Trinity Flywheel of San Francisco is intended to provide power smoothing, covering the variations in grid power that can disrupt sensitive equipment, and to provide short-term backup power in an outage.
- Team member TSI provided a prototype, production-size flywheel (see Figure 1) for telecommunications backup power to Bellcore. TSI participated with the regional Bell Telephone Operating Companies developing the generic requirements for back-up telecommunications power units to be purchased for beta sites in the next few months and for widespread deployment next year. Prices for production quantities up to one million annually have been quoted.

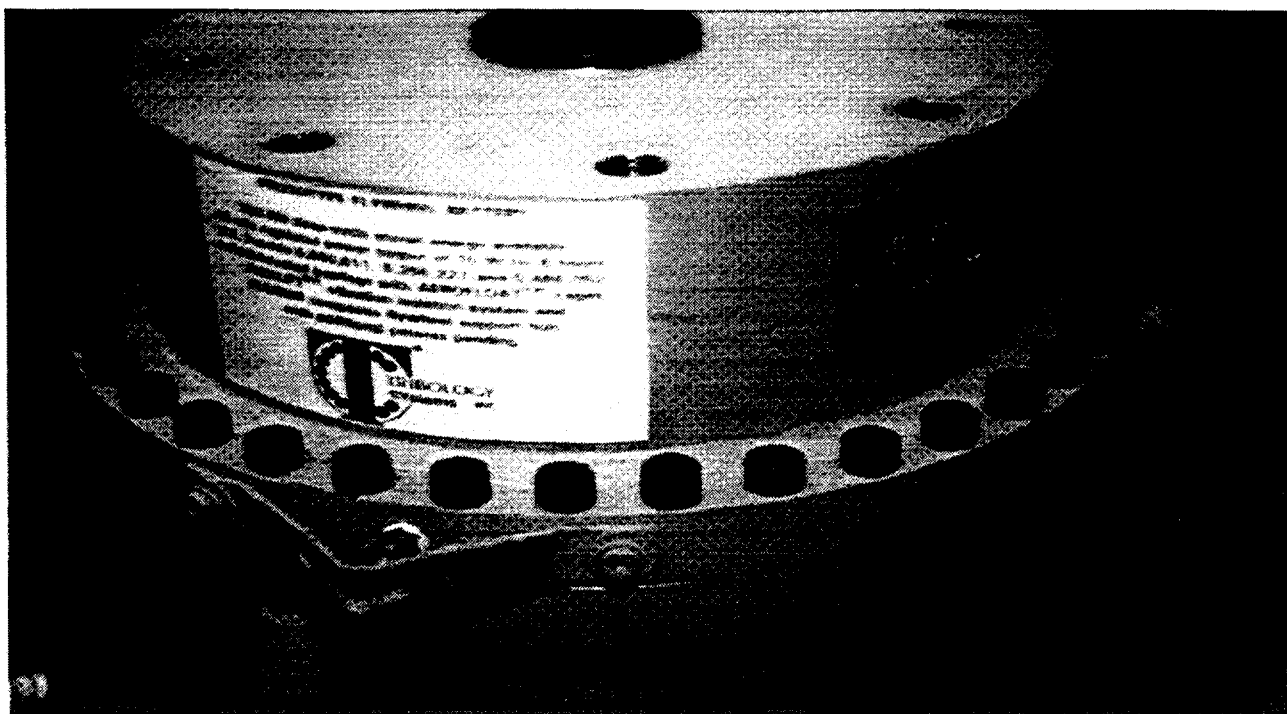


Figure 1. TSI Bellcore flywheel.

- TSI's recent application to flywheels of solid-lubricated, hybrid-ceramic bearings and sliding surfaces greatly reduced flywheel cost in comparison to designs that use magnetic bearings. This breakthrough evolved from TSI technology and products developed over three decades.<sup>1,2,3</sup> These bearings are used not only in TSI's own flywheels, but as primary or backup bearings in wheels made by United Technologies Corporation, including the units in the BMW and Air Force vehicles described above.
- Fifteen hybrid diesel-electric buses with flywheel storage and regenerative braking have been in use in Europe since 1988.<sup>4</sup> These magnet motor units store 2 kWh with 150 kW peak output. The oldest of these buses has traveled 180,000 km and its flywheel has achieved 250,000 cycles.

As these and other projects demonstrate, flywheels are much further along the development curve than ECs, particularly those ECs used in a slow-discharge energy storage mode. With one exception (Russian "traction" capacitors), large capacitors developed to date have focused primarily on fast power response, not on energy storage. The performance parameters and economics of ECs with the characteristics needed for energy storage in PV systems are basically unproven.

<sup>1</sup> Sibley, L.B., and Allen, C.M. "Friction and Wear Behavior of Refractory Materials at High Sliding Velocities and Temperatures," *Wear* 5, 312-320 (1962).

<sup>2</sup> Taylor, K.M., Sibley, L.B., and Lawrence, J.C. "Development of a Ceramic Rolling-Contact Bearing for High-Temperature Use," *Wear* 6 (3) 226-240 (1963).

<sup>3</sup> Sibley, L.B. "Silicon Nitride Bearing Elements for High-Speed High-Temperature Applications," Paper No. 5, NATO/AGARD Conference Proceedings No. 323 on Problems in Bearings and Lubrication (1982).

<sup>4</sup> Belanger, M. "Flywheels for Energy Storage Applications," 6<sup>th</sup> International Seminar on Double Layer Capacitors and Similar Energy Storage Devices (1996).

### 3.1.1. Advantages in PV Systems

Advantages and disadvantages of both flywheels and electrochemical capacitors in PV systems are defined primarily by comparing them to the present storage standard, the lead-acid battery. Although other batteries and other energy storage systems, such as hydraulic storage, compressed air, and hydrogen generation are used in PV systems, the storage workhorse of PV systems is the lead-acid battery.

Much flywheel research has focused on use in vehicles and spacecraft, leading to an emphasis on minimizing the size and weight of the unit. Thus, much work has been directed at high-speed (up to 90,000 rpm) units, which theoretically require magnetic bearings for longevity. This work has not been fully successful to date.

The size and weight constraints of the typical PV system are far less severe.

While transportation is certainly a consideration for many sites, present components (e.g., batteries) are heavy and fairly large. Because the flywheel rotor may be heavier for such systems, rotational speed may be less, and such units are farther along the development curve than high-speed wheels. The TSI wheel turns at 30,000 rpm, and has demonstrated longevity and reliability using ceramic bearings. This wheel represents the state of the art for this technology and is used as a representative flywheel in this report.

#### 3.1.1.1. Compatibility with Remote Sites

The present, and to a greater extent, the projected characteristics of flywheels make them exceptionally well-suited to the remote locations that are typical of PV power systems. In part, this is because they share many of the characteristics of the PV module. These characteristics are discussed below. Flywheels are just beginning the prototype deployment stage in remote sites. Assuming the experience is favorable, it is probable that they will assume a major energy storage role in remote power.

Lead-acid batteries are widely used but, because of their maintenance needs and replacement frequencies (every 2 to 7 years depending on various factors), are a poor fit to many remote power systems, especially when compared to the PV component. Additionally, lead-acid batteries are expensive to transport and install, use hazardous materials, can be damaged by misuse or poor maintenance, and may generate hydrogen gas.

#### 3.1.1.2. Longevity

Performance of prototype flywheels at TSI facilities and computer modeling suggest a life expectancy for TSI flywheels longer than 20 years for most applications. One TSI unit has been in operation since the 1950s without relubrication.<sup>5</sup> Present fatigue design criteria are for 100,000 charge-discharge cycles per year<sup>6</sup>, which, at one cycle per day, equates to a 274-year life span. The calculated L10 life (the period over which 10% of units would be expected to fail) is 90 years.

---

<sup>5</sup> Letters from Lewis B. Sibley of TSI to Bill Rever of Solarex. July 28, 1998 and May 5, 1999.

<sup>6</sup> Sibley, Lewis B. "Advanced Technology Ceramic Bearings in the Flywheel Systems at World Flywheel Consortium." Presented at the Flywheel Energy Storage Workshop, Oak Ridge, TN. 1995.

The L10 life is calculated using the equation:

$$L = a_1 \times a_{SKF} (C / P)^3$$

Where  $a_1$  is 1 (indicates “very clean” operating conditions) for 90% reliability,  $C$  is the basic dynamic load rating for each bearing size (based on the manufacturer’s specifications),  $P$  is the equivalent load on the bearing in service,  $a_{SKF}$  is 37 (calculated from manufacturer’s specifications). Therefore,

$$L = 37 \times 40^3$$

or 2,368 billion revolutions. At a typical 50,000-rpm continuous mean rotor speed,

$$L = 2368 \times 10^9 / (50000 \times 60 \times 8760)$$

or 90.1 years. In comparison, the batteries of a PV system require replacement at least three times, and as frequently as six times (depending on severity of cycling and thermal stresses) over what PV designers have considered the nominal lifespan of a PV system—20 years.

As experience with deployed PV systems has accumulated, major module manufacturers have gained confidence in the ability of their products to exceed this lifespan. Siemens recently extended the warranty period on their large modules to 25 years. Solarex has introduced a new series of large modules, the GSX series, with a 30-year warranty.

Furthermore, the failure mechanisms of deployed PV modules are, in general, either “infancy” failures or long-term gradual output degradation, which is not a true “failure,” although it may eventually cause inability to support the load. After infancy, modules are likely to function effectively for at least 30 years. As the PV industry has matured, the causes of infancy failures (thermal cycling of interconnects, material incompatibility, water migration, etc.) have been identified and corrected, and the failure rate has been dramatically reduced.

It is appropriate, therefore, to consider a lifespan longer than 20 years for PV systems and their components. Most of the comparisons in this report are based on a 30-year system life.

#### 3.1.1.3. Lack of Maintenance

For all intents and purposes, the TSI flywheel is maintenance free as a result of its hybrid ceramic bearings and solid lubrication system. Alternative bearing systems are either very expensive (magnetic bearings) or incompatible with operation in a vacuum. Conventional bearings require periodic lubrication, typically with volatile petroleum-based lubricants that contaminate the vacuum.

In contrast, lead-acid batteries require inspection and terminal cleaning and some require watering between two and twelve times a year, depending on cycling and thermal climate.

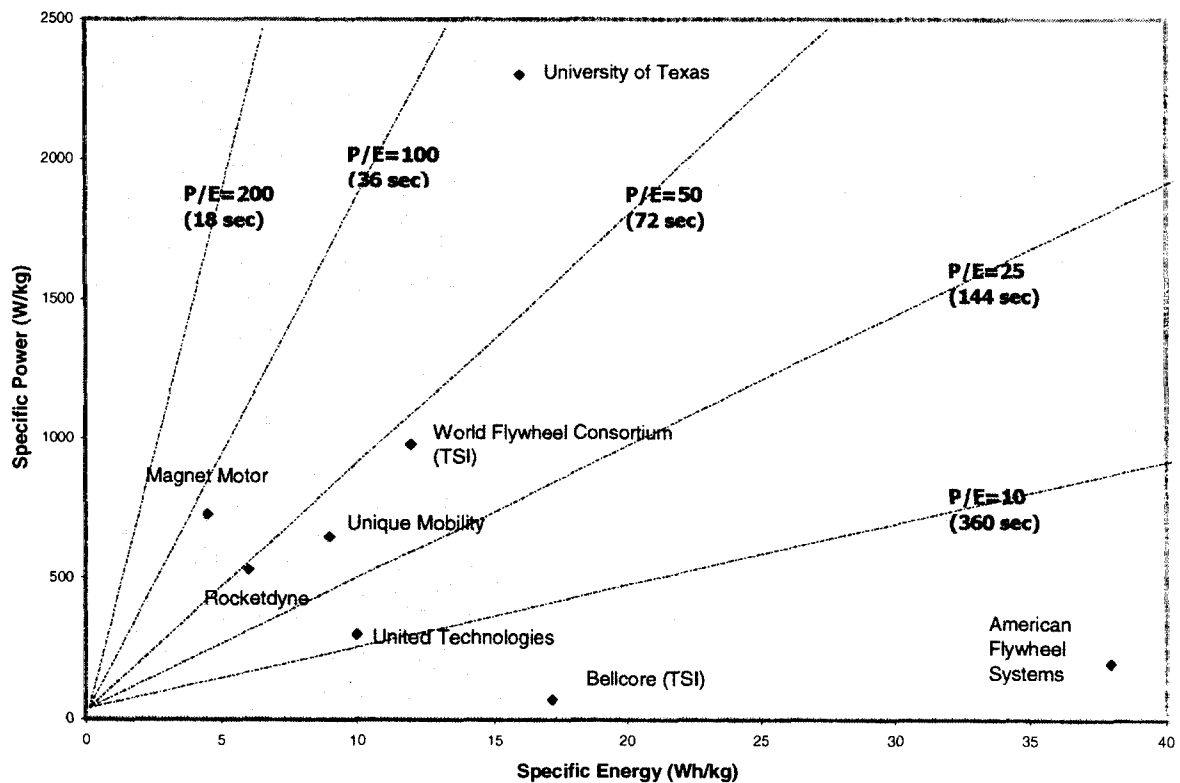
#### 3.1.1.4. Insensitivity to Deep Cycling

Even the best deep-cycle batteries suffer from shortened lifetimes if they are cycled beyond their specified depth-of-discharge limit, or are cycled frequently. These limitations force system owners and designers to trade off reliability against cost, either by using an oversized battery to ensure continuous power to the load or by including a low-voltage disconnect circuit that protects the battery but sacrifices the load.

Repeated overdischarge is catastrophic to a lead-acid battery, but flywheels are unaffected by it, both structurally and in terms of longevity and regardless of discharge frequency. This characteristic frees the system designer from the costly sizing/disconnect consideration above.

#### 3.1.1.5. Surge Capability

The ability to respond to demand surges can be both a positive and a negative characteristic of a flywheel, depending on the design of the flywheel, the duration of the surge, and the criticality of the load's power requirement. Figure 2 illustrates the specific power vs. specific energy (P/E ratio) of a number of current flywheel designs, and the characteristic durations associated with the P/E ratios.



**Figure 2. Ragone plot for P/E ratios of current flywheels.**

The flywheel's characteristic duration—the minimum period in which a device can deliver approximately 63% (the  $1-1/e$  value) of its capacity to a

load<sup>7</sup>—varies from approximately 18 seconds for a wheel with a P/E ratio of 200 to approximately 360 seconds for a wheel with a P/E ratio of 10. Some storage media are less efficient for surge (high power) requirements shorter than approximately 5 times their characteristic duration.

As Figure 2 shows, most development work has concentrated on flywheels capable of fast response, a characteristic necessary for vehicular applications and any other application where the wheel must cope with a load that may vary rapidly. It does not illustrate the characteristics of wheels that could be designed specifically for PV systems, which could have durations on the order of an hour and P/E ratios well below 10. Such wheels, and the lower P/E wheels illustrated, could not respond well to short-term demand peaks, particularly if the peaks required good power regulation.

Although PV battery banks generally have the ability to meet demand surges, if the surge is sufficiently large and repeated it will shorten the life of the battery bank. In systems that anticipate such surges, adding a fast-response flywheel or a capacitor to the power system may improve overall power quality and extend battery life.

#### 3.1.1.6. Tolerance of Ambient Temperature Extremes

With solid lubricant, TSI flywheels are unaffected by any terrestrial ambient temperature, in terms of efficiency, longevity, and storage capacity.<sup>8</sup>

Battery capacity and life is typically optimized for, and rated at an operating temperature of 25°C, and a significant variation from that temperature compromises operating life or storage capacity. Manufacturers' literature indicates that a battery's rated life is reduced by half if it is operated continuously at 35°C, and that batteries fail very quickly if operated above 50°C. Battery capacity is reduced by approximately half (from rating) at 0°C.

A discharged battery may be destroyed by subfreezing temperatures. At 80% depth of discharge battery electrolyte freezes at -10°C, resulting in permanent damage to the plates and case. A fully discharged battery freezes at only slightly below 0°C.

#### 3.1.1.7. Lack of Environmental Impact

Batteries use hazardous materials—among them lead, sulfuric acid, and cadmium—and thus present environmental concerns that must be addressed during their manufacture, use, and disposal. The materials used in flywheels have less environmental impact.

Safety concerns about containment of flywheel components in case of catastrophic failure have been addressed by several projects and studies, the most recent being a Defense Advanced Research Projects Agency (DARPA)

---

<sup>7</sup> **Note:** Not all flywheel developers use 63% as the cutoff level for energy extraction. Varying this percentage will affect the flywheel's spin down time.

<sup>8</sup> Sibley, L.B. "Silicon Nitride Bearing Elements for High-Speed High-Temperature Applications," Paper No. 5, NATO/AGARD Conference Proceedings No. 323 on Problems in Bearings and Lubrication (1982).

project that included extensive analysis in conjunction with the National Renewable Energy Laboratory (NREL).<sup>9</sup>

The high kinetic energy of a bursting flywheel is expressed almost entirely as high circumferential rubbing speeds when fragments centrifugally impact the containment housing. The containment system of the TSI flywheel used in this study is based on multiple burst tests (in all of which the rotor was completely contained) and advanced computerized testing.<sup>10</sup> Additionally, in many PV applications the flywheel can be buried, which provides redundant protection in case of flywheel failure.

### **3.1.2. Disadvantages in PV Systems**

A flywheel's disadvantages in a PV system are few but significant: cost and the development status of the technology. Substantial progress has been made since the 1960s, but current designs have yet to undergo the ultimate test of long-term deployment. Experience with PV systems indicates the potential for presently unidentified remote-site problems with the flywheel itself and the electronics that control power input and output.

#### **3.1.2.1. Cost**

Team member TSI configured four representative flywheel models in various sizes to meet the requirements of the specified systems. As with batteries, these units would be used in multiples to provide the exact amount of energy storage required for a specific system.

Table 1 shows the development costs and several production volume and timing assumptions for each of the representative models. These costs are based on TSI's knowledge of the economics of flywheel development and volume production costs associated with TSI's own flywheel technology. The comparisons between storage technologies are not adjusted for inflation or other time effects. The production volume figures are fairly aggressive estimates of total annual volume for all markets, not just those associated with PV. This report addresses life-cycle issues, inflation, and other time effects using the net present value (NPV) method described in Section 5.1.

---

<sup>9</sup> Sibley, L.B. "Design Optimization and Proof Testing of Safety Containment Systems for Flywheel Energy Storage Systems," Final Report on Subrecipient Agreement No. MARCAV 9602-12 of DARPA Contract MDA 972-95-3-0019 (1998).

<sup>10</sup> Sibley, L.B. "Design Optimization and Proof Testing of Safety Containment Systems for Flywheel Energy Storage Systems," Final Report on Subrecipient Agreement No. MARCAV 9602-12 of DARPA Contract MDA 972-95-3-0019 (1998).

**Table 1. TSI Flywheel Production and Development Cost Estimates**

	Flywheel Model & Usable Capacity			
	0.5 kWh	2.5 kWh	25 kWh	200 kWh
<b>Development Cost</b>	Negligible	\$150,000	\$350,000	\$500,000
<b>First Unit Cost</b>	\$35,000	\$65,000	\$275,000	\$450,000
<b>Production Start in:</b>	Cost Annual Production Quantity			
<b>1 year</b>	\$2200 50-80K	\$9800 30-50K	(1)	(1)
<b>3 years<sup>2</sup></b>	\$1000 300-500K	\$6800 200-300K	\$50,000 40-60K	\$210,000 3-4K
<b>5 years<sup>2</sup></b>	\$750 600K-1M	\$3200 400-600K	\$21,000 80-100K	\$90,000 8-10K
<b>10 years<sup>2</sup></b>	\$500 3-5M	\$1000 2M-3M	\$8700 400-600K	\$55,000 40-60K
<b>Lowest \$/kWh</b>	\$1000	\$400	\$348	\$275

1. Development time precludes production start in 1 year.

2. Estimates for 3 years and longer are conservative; cost could be less if volume levels are met.

The smallest unit (0.5 kWh) requires little development and could be ready for production in less than 1 year, with an initial cost, assuming production of 50,000-80,000 units per year, of \$2200. Under the 10-year, high-volume (3 to 5 million annually) assumption, these units are projected to cost \$500 or less each, equating to \$1000 per kWh.

The largest models (25 and 200 kWh) require substantial development work, estimated at 12 to 18 months; thus, no 1-year production figures are given for them. As would be expected, the largest unit, the 200-kWh model, is projected to provide the least expensive storage—\$275 per kWh under the 10-year, high-volume assumption. Under the 1-year production case, the smallest unit (0.5 kWh) provides the most expensive storage at \$4400 per kWh.

In comparison, high-quality lead-acid batteries cost approximately \$100 to \$120 per kWh. They may not, however, be fully discharged without shortening their usable life. Assuming 50% of their nominal capacity is used, their effective cost increases to \$200 to \$240 per kWh. Thus, using the 10-year production models, the projected cost of flywheel storage ranges from a high of five times as much as batteries to almost equal to that of batteries. In the short term (1 year), flywheel storage is much more expensive, up to 20 times more expensive for the smallest units.

These storage costs are based on TSI's estimates for *production* units, not prototypes. The pilot production units will be substantially more expensive than production units due to material volume considerations and the cost of custom machining and other labor-intensive production steps. These costs are reflected in the *First Unit Cost* entries in Table 1.

### 3.1.2.2. Reliability

Although, as described above, calculations of predicted flywheel lifetimes are impressive and supplement laboratory and prototype experience, long-term remote deployment is the ultimate test. The PV industry knows from experience that deployment tests the system as a system, in situations where failure of one component means total system failure.

In particular, the flywheel's control electronics require field testing. The rigors of remote-site systems—lightning, animal damage, substandard transportation, marginal installation, etc.—can wreak havoc on PV control systems that appear bulletproof on the design board.

### 3.1.2.3. Surge Capability

As previously mentioned, wheels designed specifically for PV systems (and any wheel with slow characteristic response time) cannot respond well to short-term demand peaks if the peaks require good power regulation.

Although the flywheel has sufficient energy to meet the peak, its control electronics must respond almost instantaneously to some loads (e.g., computers) to maintain nominal operation.

In addition to response time and power quality considerations, a flywheel's electrical response is limited by the size of its power-handling conductors. Motor-generator windings must be sized to handle surge requirements, which could be impractical for some loads. Additionally, the heat generated by any component inside the containment vessel presents a dissipation requirement. For these reasons, an EC may be a worthwhile addition to many remote power storage systems, particularly those which could have substantial surge requirements.

## 3.2. Electrochemical Capacitors

ECs have achieved substantial acceptance in the electronics industry, replacing backup batteries in many complementary metal-oxide semiconductor (CMOS) memory applications. Many commercially available ECs are directed at this market, and, consequently, are of limited size and power performance. These limitations are not inherent in the technology but rather due to the market forces that have driven the design. Much larger, higher-voltage capacitors with greatly enhanced power performance have been available for several years from some suppliers and currently are being developed by others. These ECs are directed at new markets, among them automotive starting, lighting, and ignition circuits and, in Russia, vehicle motive power.

One early Russian application of ECs was for starting vehicles in cold climates. In Siberia, the cold-weather advantages of ECs over chemical batteries were quickly apparent. In addition, the Russian firm ESMA now has over two years' experience using ECs as the sole energy source for forklifts, electric trucks, and buses. The Russians are presently operating six 1.5-ton trucks, three buses, two street-sweepers, and twenty forklifts with ECs serving as the motive batteries. Additional details of

their experience are described in "New Ultracapacitors Developed by JSC ESMA for Various Applications."<sup>11</sup>

Major automotive manufacturers have been developing EVs to meet zero emission vehicle requirements. Domestic manufacturers have also been developing HEVs through sponsorship by the federal government under the "Partnership for a New Generation of Vehicles" (PNGV). In addition, transit bus manufacturers have programs to develop hybrid-electric buses (HEBs). One such program is the Advanced Technology Transit Bus or ATTB being developed by Northrup Grumman Corporation.

High-energy-density capacitors have been identified as an enabling technology for many of these low-pollution applications, and recent development efforts have focused primarily on EC technology. ECs appear well suited for such applications because they offer high volumetric capacitance density. This advantage is derived from the use of high-surface-area electrodes to create a large "plate area" and from storing energy in the so-called diffuse double layer. This double layer, created naturally at a solid/electrolyte interface when voltage is imposed, has a thickness of only approximately 1 nm, forming an extremely thin "plate separation." Consequently, ECs with very high capacitance density can be made using high-surface-area electrodes. Some ECs show enhanced capacitance derived from pseudocapacitance charge storage in addition to double layer charging. One Russian company manufactures an asymmetric EC having energy density greater than 10 Wh/kg.

Compared to batteries, ECs have longer cycle life and higher rate capability, but lower energy density. They require a much simpler charging circuit than a battery, and display no "memory effect." Physical, rather than chemical, energy storage is the key reason for the EC's cycle life and its high power density compared to other capacitors. Furthermore, ECs have the potential to meet important cost targets because their electrodes typically consist of relatively low-cost material, for example, activated carbon derived from wood or coal.

Significant advances have been made in the development of large capacitors during the past decade, stimulated by Isuzu's 1990 development of a "revolutionary new battery." Some investigations have focused on using ECs to level the load on energy storage systems in electric and gas-electric hybrid vehicles, reducing stress on the chemical batteries and extending their life. Other development activities, funded primarily by the U.S. Department of Energy (DOE), have been directed at starting internal combustion engines, electrically preheating exhaust catalytic converters, powering uninterruptible power supplies (UPSs), and other automotive applications.

Most of these applications require large capacitors capable of delivering a substantial fraction of their stored energy in a few seconds. This power performance requirement is a major departure from the established computer memory backup applications, where discharge times are typically hours or days. These design drivers are similar to

---

<sup>11</sup> Varakin, I.N., Klementov, A.D., Litvinenko, S.V., Staroduvtsev, N.F., Stepanov, A.B. "New Ultracapacitors Developed by JSC ESMA for Various Applications," 8<sup>th</sup> International Seminar on Double Layer Capacitors and Similar Energy Storage Devices (1998).

energy system drivers where an EC would meet power surges, but very different from system drivers where an EC would be the primary energy storage medium.

Team member JME used published data, correspondence, and discussions with developers and manufacturers to compile a summary of products and technologies of various vendors (see Appendix A). Manufacturers' addresses are included as Appendix B.

### **3.2.1. Advantages in PV Systems**

Electrochemical capacitors have significant advantages for deployment in PV systems, particularly in remote settings.

#### **3.2.1.1. Lack of Maintenance**

In contrast to the battery maintenance requirements described previously, capacitors require no maintenance. The financial and systemic ramifications of this are enormous, greatly reducing system cost over time and allowing the storage system to be located in places impractical for chemical battery systems (e.g., buried).

#### **3.2.1.2. Longevity**

Because capacitors store charge physically rather than chemically, cycling has virtually no effect on their capacity or longevity. The lifetime of most capacitors is limited by electrolyte loss. Twenty-year life is easily achieved by proper selection of materials and control of operating parameters. It is anticipated that thirty-year life is also achievable, although this will require development and may increase product cost.

#### **3.2.1.3. Environmentally Benign**

Capacitors do not employ toxic materials, and thus present no environmental threat in manufacture, transport, or disposal. They do not outgas in use and present no threat of explosion.

#### **3.2.1.4. High Discharge Rate Capability**

Capacitors can be discharged at very high rates without damage. High rates, however, reduce the delivered energy of the unit.

### **3.2.2. Disadvantages in PV Systems**

#### **3.2.2.1. Self-discharge Rate**

The self-discharge rate of most capacitors is substantially higher than that of batteries or flywheels. This limits their application in grid-independent settings to systems with multiple storage media capable of offsetting this self-discharge. In grid-connected systems, where they could serve to attenuate drastic demand swings, self-discharge is not a major consideration.

Team member JME indicates that the self-discharge of the ESMA EC is lower than that of any other capacitor type. It is expected to take 8 months to discharge to 50% of capacity. This is very similar to the rate for some shallow-cycle batteries, which can lose up to 6% per month to self-discharge. (Good deep-cycle batteries are substantially better.)

Battery self-discharge is usually of little consequence in PV system sizing because its magnitude is small enough to be hidden in procedures necessary to account for solar variation. If self-discharge in ECs proves to be high, however, it would have to be compensated for in system sizing procedures, and should be quantified in any further investigations.

#### 3.2.2.2. Cost

JME's original estimates of the cost of appropriate EC storage for PV applications were in the range of \$10 to \$20 per kJ, or \$10,000 to \$20,000 per MJ, based on extrapolating current EC costs to higher production levels with modest technological advances. At this price, between 12 and 30 times that of batteries, capacitors appeared unattractive in economic terms, particularly as straight replacements for batteries, despite the favorable characteristics discussed above.

However, during the course of this study, major Russian firms that specialize in manufacturing large ECs were asked to provide price estimates based on modifying typical EC design drivers (power delivery and response time) to drivers compatible with stand-alone PV systems, greatly reducing the need for volume power and eliminating the requirement of fast response.

ESMA's response, quoted below, cut projected purchase cost to 50 cents per kJ. The NPV analysis (discussed in Section 5.1), which includes such factors as the cost of periodic battery servicing and replacement, indicates that a capacitor selling at this price would provide storage at about three times the cost of batteries.

ESMA states:

*Given certain relaxed constraints as per your information, we may concentrate on "traction" capacitor technologies. These technologies allow [us] to ensure lower prices per 1 kJ of energy. If compared to prices for batteries (per your information – U.S. \$120 per 1 kWh), the pinnacle of our desires today with respect to "traction" capacitors is about U.S. \$1700-1800 per 1 kWh (which corresponds to U.S. cents 47-50 per 1 kJ). Again, the foregoing levels may be reached only in case of large-scale batch production and under cheaper electrode production technologies. These prices are currently several times higher.*

This projection is preliminary, and is subject to all the technical and economic uncertainties that affect a technology as new as ESMA's. While the Russian experience is promising, there are many steps between ESMA's current product status and the deployment of ECs as a component in a cost-effective, reliable PV power system. These steps include developing a less costly electrode production method, scaling up production significantly, prototyping, and field testing.

Additionally, the volatility of the present Russian economy and currency make this cost projection less certain than if it had been offered by a firm located elsewhere. However, regardless of the country of origin, the offer represents the state of the art in large traction ECs today. If ESMA does not

apply its knowledge to producing PV-compatible ECs in Russia, firms in other countries probably will.

#### 3.2.2.3. Output Voltage Control

Although the output of a PV device is well-suited to charging a capacitor, capacitor discharge characteristics are significantly different than lead-acid battery discharge characteristics. Battery voltage drops slowly under load until a substantial portion of the battery's usable energy has been extracted. In a typical PV application, battery voltage drops about 11% as 90% of its energy is extracted.

Extracting 75% of a battery's energy produces a voltage drop of 7 to 8%. In contrast, extracting 75% of an EC's energy produces an approximately 50% voltage drop. The consequence is a broad voltage swing, which severely limits the applications to which ECs may be applied without power conditioning.

Many present PV applications require no power conditioning or voltage limiting. These loads tolerate the voltage swings of the battery as it charges and discharges. A virtue of such systems is their simplicity—with no circuitry between the battery and the load other than a high-reliability switch (used primarily to protect the battery from deep discharge) their failure modes are limited. In fact, some critical systems have no active element between the battery and the load, valuing load support above battery longevity.

Virtually all traditional PV applications would require power conditioning between the output of an EC and the load, either a DC/DC converter for DC loads or an inverter for AC loads. This requirement adds to system cost and reduces system efficiency and reliability.

The corollary to the voltage range of a discharging capacitor is its available energy. Although discharging an EC below 50% of its rated voltage does not harm its structure, for most applications additional discharge is impractical. Thus a capacitor's available energy is typically only 75% of its rating.

### 3.3. Capacitor/Flywheel/Battery Combinations

Quantifying the efficacy of flywheels and ECs as storage media in PV systems is difficult. Although the EC's energy storage capability has been known for a century, no real market existed until the development of low-current-draw volatile computer memory circuits. Most development and commercialization effort has focused on this market and on improving the device's response speed and short- and mid-term energy storage characteristics. With the exception of recent Russian efforts, little has been directed at optimizing ECs for the characteristics important to PV systems, particularly efficient long-term energy storage.

The little development that has been done in this area indicates that ECs not only can be substantially improved for this purpose, but that their cost per joule can be reduced substantially in the process. Cost reductions can be effected because of reduced labor and inherent efficiencies of scale. Further, per joule, long-term storage requires more of the EC's active elements (primarily carbon) and less of the inactive elements (i.e., packaging, separators, current collectors, interconnect bus sizes, etc.), which are generally more expensive than the active elements.

Flywheels have progressed much further towards integration into PV power systems, but their recent development has been so rapid that in-system performance projections are difficult. The following are among the most important developments:

- Development of graphite fiber rotor materials with dramatically improved strength and energy storage capability (see Table 2).
- Demonstration of product safety, with rotor fragments fully contained in DARPA burst testing.
- Demonstration of low-friction, solid-lubricated, non-magnetic bearings.

**Table 2. Characteristics of Flywheel Rotor Materials**

	<b>Composite Strength* (Gpa)</b>	<b>Composite Density (kg/m<sup>3</sup>)</b>	<b>Theoretical Max Specific Energy (Wh/kg)</b>	<b>Relative Max Specific Energy (Steel=1.0)</b>
<b>Graphite fiber (1995)</b>	4.8	1609	414	11.2
<b>Graphite fiber (1989)</b>	3.4	1609	293	7.9
<b>S-glass (fiber)</b>	2.1	2190	133	3.6
<b>E-glass (fiber)</b>	1.8	2205	113	3.1
<b>Maraging steel</b>	2.1	7860	37	1.0

\* Ultimate strength for fibers, yield strength for steel

Although flywheels have been used in demonstration projects (primarily in transportation applications) since the 1960s, the wheels have used a great variety of materials and components and the experience gained is only partially applicable to state-of-the-art units. Such units (for example, the TSI unit presently being tested by Bellcore) have not yet established a field operating record, and their characteristics in PV systems cannot be projected precisely. The important parameters yet to be established include the following:

- The ability of the control electronics to cope with varying loads, particularly surges;
- The ability of the control electronics and other subsystems to cope with the environmental extremes (e.g., lightning) of remote sites; and
- The ability of the bearings and other subsystems to make the transition from the laboratory environment to the range of transportation and installation conditions faced by PV systems (e.g., multi-G shock loads imposed by 4-wheel vehicle transport on poor roads, deployment in developing countries).

Despite our present inability to quantify these performance and cost factors accurately, we feel that the synergies below are promising and bear additional investigation.

### **3.3.1. Flywheel/EC Systems**

Although flywheels respond quickly to demand, their characteristic response time is longer than an EC's, which can cope with the millisecond-level response required by such applications as UPSs. The motor-generators of many existing flywheel systems, including those manufactured by TSI, use an electrolytic capacitor for starting and to smooth transients. Replacing this capacitor with a high-capacity electrochemical unit could, in addition to the electrolytic's function,

- greatly improve the system's ability to respond to demand surges and simultaneously relax the design requirements for the mechanical components of the flywheel system; and
- extend the unit's life substantially. Present electrolytic capacitors last, at best, 10 years. ECs can be made for 20- or 30-year lifetimes, a span compatible with the demonstrated life of PV arrays and the expected life of flywheels.

### **3.3.2. Battery/EC Systems**

Batteries have the ability to provide extremely high power levels on demand. Although most PV applications make no use of this characteristic, other battery applications do. One such application is telephone substations, which use large batteries to maintain service during utility power outages. These batteries are cycled infrequently, but heavily, and must cope with large surge requirements. They display short lifetimes, sometimes as short as one year.

These substations are one example of grid-supplemental systems, which includes the category of UPS systems. UPSs vary tremendously in size, from units serving individual computers to systems supporting vital circuits in large buildings or building complexes. By definition, these systems must respond instantly to power outages, and often rely on battery banks to bridge the period between loss of grid power and delivery of backup power from their fuel-powered generators. These "bridge" batteries are severely cycled, subjected to heavy surge demands, and are short-lived.

Electrochemical capacitors paralleled with these battery banks could respond quickly to bridge power needs, cope with the transients generated during source changeover, absorb demand surges that would otherwise stress the batteries, and greatly extend battery life.

Intentionally left blank.

## 4. Applications

The analysis of applications began with the identification of seven application categories that are either established or emerging markets for PV systems with conventional energy storage. The examples range tremendously in scale, from systems with 5-W arrays to systems with 1-MW arrays.

These applications are summarized in Table 3. The first four applications are small- to mid-size systems with well-established markets. The last three applications are larger and address markets that can be characterized as rapidly developing. Although numerous examples of grid-connected commercial and transmission and distribution (T&D) support systems exist, most are prototypes or are supported by corporate or government development programs.

This section discusses the application categories and the system sizes necessary to meet their requirements. Example system configurations, based on the representative flywheel sizes discussed in Section 3.1.2.1, and consisting of a PV array, a flywheel or multiple flywheels, and an electrochemical capacitor attached to each flywheel are provided for reference. The ECs in these example systems would provide limited energy storage to cope with transients, provide fast response to demand surges, and maintain power quality. These ECs are sized to provide up to half of the load's peak demand for three seconds. This capacity is sufficient to support a significant surge in a stand-alone PV system. As a point of reference, the Electric Power Research Institute (EPRI) reports that approximately 92% of line "voltage sag" events last three seconds or less.<sup>12</sup>

While we highly recommend further investigation into the role of ECs as a primary energy storage medium, we do not have sufficient data at present to configure them, even conceptually, as a system's sole energy storage device.

**Table 3. Application Categories for PV Systems**

<b>Application</b>	<b>Input to Storage</b>	<b>Output from Storage</b>	<b>Nominal Capacity</b>	<b>Temperature Range</b>	<b>Potential Market</b>
<i>Instrumentation/ Highway Call Box</i>	5-30 W @ 12 V	Continuous 1-5 W @ 12 V; Max 100 W	50-600 Wh	-40°C-60°C	50K/yr
<i>Grid-independent Residential</i>	30-120 W @12 V	Max 200 W	500-2500 Wh	-10°C-40°C	100K/yr
<i>Telecommunications</i>	500 W-5 kW 80% @ 48 V 20% @ 24 V	Continuous 25-500 W; Max: 1 kW	5-100 kWh	-25°C-40°C	1000/yr
<i>Grid-connected Residential</i>	1-5 kW @ 48 V, 120 V, 240 V	5 kW	5-30 kWh	10°-30°C	10K/yr
<i>EV Charging Station</i>	25 kW-50 kW	50 kW-100 kW	1-2 MWh	Ambient	100/yr
<i>Grid-connected Commercial</i>	25 kW-500 kW	Continuous same as PV array; Max: 300 kW-1 MW	0.2-2 MWh	Conditioned	50/yr
<i>T&amp;D Support</i>	200 kW-1 MW	Continuous same as PV array; Max: 500 kW-2 MW	2 MWh	Ambient	10/yr

<sup>12</sup> EPRI Distribution Power Quality Report #RP3098-01.

#### **4.1. Instrumentation/Highway Call Box**

This group represents a number of small PV applications. These are applications where a small amount of power is needed for small electronic devices such as instruments, sensors, data loggers, radio telemetry transceivers, or cellular phones. These applications typically require from 5 to 50 Wh per day, which can be generated by 5 to 30 Wp of PV.

System configuration example: One 0.5-kWh flywheel and a 2.4-kJ EC.

#### **4.2. Grid-independent Residential**

Systems of this scale can be remote vacation-type cabins or homes in developing countries and developing sections of the U.S. and other industrial countries. Such systems have been deployed in Africa, Asia, U.S. Indian reservations, and other low-energy homestead locations.

A persistent problem in these applications—particularly in those areas where residents are not personally involved in selecting and financing the systems, and where residents do not understand the system's characteristics—is battery abuse. The services provided by the system (lighting, television, refrigeration) are valued and are heavily used—so heavily that it is common for batteries to be deep-discharged with such frequency that their life is very short. Agencies involved in providing these power systems specify low-voltage disconnect circuits intended to prevent deep discharge, but residents commonly wire jumpers around the disconnect switch, defeating its intended purpose. Consequently, this application needs storage that will not be harmed by deep discharge, which makes it a promising application for flywheel-based storage.

This application was specified as including PV arrays with outputs ranging from 30 W to 120 W and battery storage between 500 Wh and 2500 Wh. It is important to note that this storage is expressed traditionally as nominal battery capacity. Given the realities of battery characteristics and use, actual usable capacity is about half these figures.

System configuration example: One to three 0.5-kWh flywheels each with a 2.4-kJ EC.

#### **4.3. Telecommunications**

The range of applications in this category would use PV arrays with peak outputs between 500 W and 5 kW.

System configuration examples: 5-kWh system—two 2.5-kWh flywheels each with a 6-kJ EC, *or*, 100-kWh system—four 25-kWh flywheels each with a 20-kJ EC.

#### **4.4. Grid-connected Residential**

The range of applications in this category would use PV arrays with peak outputs between 1 kW and 5 kW. Mid-sized flywheels (2.5 kWh to 25 kWh) with appropriately sized ECs (6 kJ to 20 kJ) could be configured to meet the requirements of this application.

#### **4.5. Electric Vehicle Charging Station**

This application would use PV arrays with peak outputs between 25 kW and 50 kW.

System configuration example: Five to ten 200-kWh flywheels each with a 160-kJ EC.

#### **4.6. Grid-connected Commercial**

This range of applications would use PV arrays with peak outputs between 25 kW and 500 kW.

System configuration example: One to ten 200-kWh flywheels each with a 160-kJ EC.

#### **4.7. T&D Support**

One example of this application is a community located at the end of a single transmission line whose capacity, adequate at most times, is strained by peak loads. Such situations are not uncommon; a good example is an island community with growing population.

The power systems specified in Table 3 include flywheel storage of 2 MWh with PV arrays providing between 200 kW and 1 MW. Even without the PV array, this system could provide substantial peaking capability. The flywheels (or flywheel) could be fully charged during off-peak hours with grid power available, because of timing, at the lowest possible rate. The flywheels would then make this power, generated by efficient plants during low-cost periods, available in an energy-strapped community during peak hours.

The PV array would extend the capability of the system, using similar principles. With peak output at solar noon, the array would assist in fully charging the flywheels. The array would typically provide significant (though not peak) output throughout the afternoon, contributing to community's energy needs and conserving the flywheel's capacity for the late afternoon peak.

System configuration example: Ten 200-kWh flywheels each with a 160-kJ EC.

Intentionally left blank.

## **5. Market Analysis**

### **5.1. Net Present Value Analysis**

A spreadsheet was used to analyze the costs over time of various system configurations. This analysis provided the cost comparisons that are referenced in other sections of this report.

We analyzed three comparable systems using the lowest projected costs for a nominal 1-kW PV system. The primary differences are in the first costs of the storage systems and in their placement and maintenance. It was assumed that the power electronics for all of the systems would need replacement every 10 years, the chemical batteries would need to be replaced every 7 years, and the flywheel systems would be maintained at 5-year intervals with an annual inspection. Chemical batteries were also assumed to be maintained once per year. A 30-year system life was assumed, corresponding with the nominal design life of the PV modules.

The NPV method was used to compute the life-cycle costs of the three systems. In this method, the time value of money is accounted for by discounting future cash flows at a fixed discount rate. This rate is the owner's after-tax cost of capital, and will vary with the type of entity owning the equipment; the owner's tax status, credit worthiness, and risk preferences; and the capital market situation in the country where the system is installed. A typical rate at the present time for U.S. corporations is 10%, so this rate was used in the analysis. Higher rates reduce the value of future costs and therefore make systems with lower initial costs but higher operating costs more favorable. Lower rates have the opposite effect – making future costs relatively more significant.

The NPVs of the flywheel/EC system and the lead-acid battery system with a 10% discount rate are close enough to be comparable, given the uncertainty over the future costs of the systems. The analysis clearly shows that the new systems have the potential to compete effectively with chemical storage in PV applications and, as discussed below, to extend the range of PV applications.

Given these assumptions, a system with a 1-kW array and nominal chemical battery storage of 25 kWh (approximately 8 days) results in NPVs of \$18,200 for the lead-acid system, \$16,600 for the flywheel system, and \$52,700 for the system with EC storage only. A printout of this example is included as Appendix C.

### **5.2. Potential Markets**

The potential applications for the advanced storage technologies can be divided into three broad categories:

- Current PV applications that would be compatible with or enhanced by the new type of energy storage.
- Emerging PV applications that would also be compatible with or enhanced by an advanced energy storage technology.
- Applications that primarily require energy storage but might be complemented by PV.

Some overlap could exist between the second and third categories, as a number of the emerging PV applications derive value from reducing the effects of peak loading on the generation, transmission, or distribution of electricity. The applications identified here generally fall into the first and second category, as these markets are the best understood.

The potential markets that were shown in Table 3 are an estimate of what could reasonably be achieved within 5 years assuming that reliability, performance, and cost goals are achieved. The following sections discuss each of these potential markets in detail.

#### **5.2.1. Instrumentation/Highway Call Box**

This group represents a number of small PV applications that require a small amount of power for small electronic devices such as instruments, sensors, data loggers, radio telemetry transceivers, or cellular phones. In most cases the equipment is in a remote area or the power requirement is so small that it is less expensive to install a small PV system than to make a connection to the utility grid. These applications typically require from 5 to 50 Wh per day, which can be generated by 5 to 30 Wp of PV. Today, these applications are served by chemical storage batteries, most of which are the valve-regulated lead-acid (VRLA) type. Depending on the type of battery, the installation of the equipment, and the climate, these batteries will typically have a 2- to 5-year service life, although a service life as short as 1 year can occur in hot climates where the batteries are in enclosures exposed to the sun. In these situations, the life-cycle cost of the system is driven by the battery replacement cost, and energy storage systems with substantially higher first costs could be tolerated if they possessed longer lifespans. This characteristic is expected for both the ECs and the flywheels.

An estimate of market potential was developed by looking at today's market for this type of PV system and assuming a certain penetration could be achieved over time. The market for this type of system today is approximately 3 MW of PV per year with an average system size of about 15 W, or roughly 200,000 systems per year. A growth rate of about 15% means that the market will double in 5 years to 400,000 systems. Nevertheless, this may be a conservative estimate, both in terms of the underlying PV market and also because further market expansion may occur if better storage systems become available. Clearly some applications of this type have not used PV because of the weaknesses of conventional battery systems.

The principal advantages of the EC and flywheel in this application are their extended cycle life and performance over a wider range of operating temperatures. These features could extend the use of PV in this application. The disadvantages could be higher weight and/or bulk, especially when the containment for the flywheel systems are considered. This added size could be turned into an advantage in some situations, where the larger units might present a barrier to theft.

### **5.2.2. Grid-independent Residential**

Systems in this category account for about one third of today's PV market, or (according to industry reports) roughly 40 MW of PV in 1998. The average system size is about 80 W, which translates to sales of about 500,000 systems in 1998. Annual growth rates in this segment have averaged 15 to 20%, at which rate the market will at least double in the next 5 years.

This market has two distinct segments: systems on remote homes in industrialized countries and systems for basic household needs in developing countries. While the basic characteristics of these systems are similar, there are substantial differences in the system components and the approach to the market.

If the advanced storage systems achieve a life-cycle cost comparable to chemical batteries, systems with advanced storage will certainly be able to penetrate both segments of the market, especially in the industrial countries where long-term financing is available and the labor costs of replacing conventional batteries are high. It seems reasonable to expect a 10% share of this market if the objectives are met, giving a potential of 100,000 units per year.

In this category of applications, the principal advantages would be the greatly reduced maintenance and the long life of the EC and flywheel systems. The principal disadvantage would be the higher first costs, especially in developing countries where interest rates are high and financing is hard to obtain.

### **5.2.3. Telecommunications**

Telecommunications is the largest single market for PV, accounting for roughly 20 MW in 1998 based on industry reports. Applications range widely, from small rural subscriber telephone systems to microwave repeaters, cellular sites, and satellite earth stations. Roughly half of this market falls into the range of 500 to 5,000 W of PV with the average size of these systems around 2 kW; meaning that 5,000 systems will be sold in 1998. (Smaller telecommunications systems were discussed in Section 5.2.1).

This market is also growing at about 15% per year, thus doubling over the next 5 years to 10,000 systems. It seems reasonable that a 10% penetration could be achieved if advanced storage systems reach parity with chemical storage batteries on a life-cycle cost basis, which gives a potential market of 1,000 systems per year.

The advantage of wider operating temperature range and longer maintenance intervals over chemical storage batteries could extend the range of potential PV use in this application. The cost of replacing batteries in this segment could also be very high, giving an edge to the longer-lived storage technologies. The disadvantages would be potentially higher weight and bulk, and also higher first costs. Because many telecommunications systems only have 10- to 20-year life cycles due to technological obsolescence, it could be hard to justify substantially higher first costs.

#### **5.2.4. Grid-connected Residential**

Grid-connected systems are the fastest growing segment of the PV market and now represent over 30% of the world PV market, or about 40 MW in 1998. Over 80% of these systems are on homes. The average size is about 3 kW, giving a market of about 10,000 residential systems in 1998. This segment is growing at over 30% per year and in 5 years is estimated to be approximately 50,000 systems per year. Currently, most of these systems do not incorporate storage, but over half of the users surveyed have expressed an interest in storage. Present battery technology has not been attractive primarily because of the hazardous nature of chemical batteries and the need for multiple replacements over the life of the system.

Incorporating storage into these systems is desired by many homeowners to provide backup power in the event of an outage and could become a key selling feature of the systems. In fact, the backup system could be popular without the PV. Using systems such as the EC and flywheel that can tolerate extensive cycling would also enable true peak shaving, by shifting the power from midday to later in the afternoon. This could encourage the acceptance or even purchase of PV systems by utilities. Another segment that could be accelerated by adding this kind of storage is grid-connected systems for homes in developing countries. Many upper- and middle-class homeowners in these countries have access to the grid, but power is very unreliable, in some cases operating only a few hours per day or a few days per week. These homeowners have expressed substantial interest in PV systems with storage that would eliminate the reliability problems of the grid.

The advantages of the new storage systems over conventional batteries are much longer life, better cycling ability, and elimination of hazardous materials from the home. The disadvantages would be the higher first cost, and the containment required for the flywheel systems.

#### **5.2.5. EV Charging Stations**

There are about a dozen PV-powered EV charging stations operating in the world today, but it would be difficult to call this small number a true market. These systems have generally been installed on parking garages or other facilities owned by electric utilities as demonstrations. Electric utilities are promoting the use of electric vehicles as the normal operating cycle of the vehicles (used during the day, charged at night) will add to kWh sales while taking advantage of generally underutilized nighttime capacity. Electric vehicles are being promoted and even mandated in some areas to lessen air pollution; however, some environmentalists are skeptical, claiming that charging the EVs from fossil-generated electricity is simply moving the pollution from one place to another. Solar charging stations overcome this objection and demonstrate that EVs can truly represent a sustainable alternative to the internal combustion engine. Although EV mandates have recently been pushed back in some states, it is likely that tens of thousands of EVs will be in use by the middle of the next decade. As these vehicles begin to populate the highways, there will also be a need for roadside charging stations to assist vehicles running low on power. Taking all of these variables together we

believe there could be a market for 10 systems per year by the middle of the next decade.

The flywheel and EC storage systems present a major advantage in this application because of their extensive cycling capability and the ability to discharge rapidly without damage. This application would be substantially limited if only chemical storage batteries are available. There are really no disadvantages to the advanced storage systems in this application.

#### **5.2.6. Grid-connected Commercial**

The grid-connected market for PV, as previously discussed, is approximately 40 MW per year and is growing at over 30% per year. While the majority of the market is for residential systems, the balance is mainly on commercial buildings, a market of 6 to 8 MW per year.

This segment is also growing rapidly and will probably reach 25 MW in 5 years. The average system size is about 50 kW, which translates to sales of 500 systems per year in 5 years. Few of these systems are using energy storage today. As in the residential segment, there is considerable interest in systems that can provide back-up power during an outage, and in systems that can be used to shave peaks. Both of these capabilities have measurable economic value in commercial buildings. Given these considerations it seems reasonable to project that if cost and performance targets are met, the advanced storage systems could achieve a 10% penetration of this market, or 50 systems per year in a 5-year period. As with residential systems, the ability to supply backup power will probably extend the range of application of these types of systems, especially in developing countries.

The advantages of long life and extreme cycling capability will allow storage to be used in these systems where it has typically not been used before. There are no substantial disadvantages in this application (assuming cost effectiveness is achieved).

#### **5.2.7. T&D Support**

In the last ten years, half a dozen PV systems have been installed to provide T&D support. Essentially these systems are arrays placed at substations to provide additional power and voltage support where existing transformers and possibly T&D wiring are taxed during peak load periods. This application is a vast potential market for PV. At a PV price of \$3 per Wp AC, it has been estimated at over 4 GW. PV prices are currently about double that, so today's applications have largely been demonstrations.

This market segment will also see considerable competition from other technologies (e.g., microturbines and other energy storage systems). This market segment is real, but it is hard to differentiate between PV generation and energy storage systems. Energy storage systems, including banks of flywheels or ECs, could store grid energy during off-peak hours and discharge it to meet peaks. PV could enhance this function by providing more energy or, to the extent PV output and peak demands overlap, by reducing the amount of storage capacity needed. Given the limitations on this market we have estimated a potential market of ten systems per year. There could actually be more market for the storage systems, but it largely depends on the available alternatives.

### 5.3. Market Scale

Table 4 shows the projected 5-year flywheel market totals for the applications described, and the assumptions underlying the projections. For those applications served by a range of system sizes (e.g., telecommunications, with systems ranging from 5 kWh to 100 kWh), an estimate representing an average was used. Summing the last column of Table 4 by unit size gives the market projections shown in Table 5.

**Table 4. Flywheel Market Projections Based on TSI Flywheels**

<b>Application</b>	<b>Flywheel Units per System</b>	<b>5-yr Flywheel Cost Projection</b>	<b>Potential Market</b>	<b>Flywheel Volume</b>	<b>Potential Market (\$)</b>
<i>Instrumentation/ Highway Call Box</i>	1 @ 0.5 kWh	\$750	50K/yr	50K	\$37.5M
<i>Grid-independent Residential</i>	1-3 @ 0.5 kWh	\$750	100K/yr	200K	\$150M
<i>Telecommunications</i>	2 @ 2.5 kWh	\$3200	1K/yr	1K	\$3.2M
	4 @ 25 kWh	\$21,000		2.5K	\$52.5M
<i>Grid-connected Residential</i>	4 @ 2.5 kWh	\$3200	10K/yr	30K	\$96M
	4 @ 2.5 kWh + 1 @ 25 kWh	\$21,000		5K	\$105M
<i>EV Charging Station</i>	5-10 @ 200 kWh	\$90,000	100/yr	750	\$67.5M
<i>Grid-connected Commercial</i>	1-10 @ 200 kWh	\$90,000	50/yr	250	\$22.5M
<i>T&amp;D support</i>	10 @ 200 kWh	\$90,000	10/yr	100	\$9M

**Table 5. Projected 5-year Annual Flywheel Market Size Based on TSI Flywheels**

<b>Example Flywheel Size</b>	<b>5-year Annual Flywheel Market</b>
0.5 kWh	\$187.5M
2.5 kWh	\$99.2M
25 kWh	\$157.5M
200 kWh	\$109M

Projections of the market size for capacitors are substantially less certain due to the infancy of the EC technology for these applications. The financial ramifications are illustrated in Table 6, which shows the contrast in near-term (1-year) and projected 5-year costs for the ECs to be included in the four systems. JME, the capacitor consultant for the Solarex team, believes that the 1-year EC costs are best estimated at between \$30 and \$70 per kJ, with the cost increasing as the capacitor size drops. However, applying the updated ESMA cost projections to these capacitors ("5-year cost") produces far lower costs, by factors of up to 60.

The capacitor volumes generated by our projected PV-related production (the total of all applications shown in Tables 4 and 5) would not be sufficient to drive EC costs down to the 5-year cost levels shown in Table 6. These costs will be achieved only if ECs prove to be worthwhile replacements for chemical batteries in applications such

as those now demonstrated in Russia. If that occurs, EC production volume will skyrocket and costs may fall to the projected level.

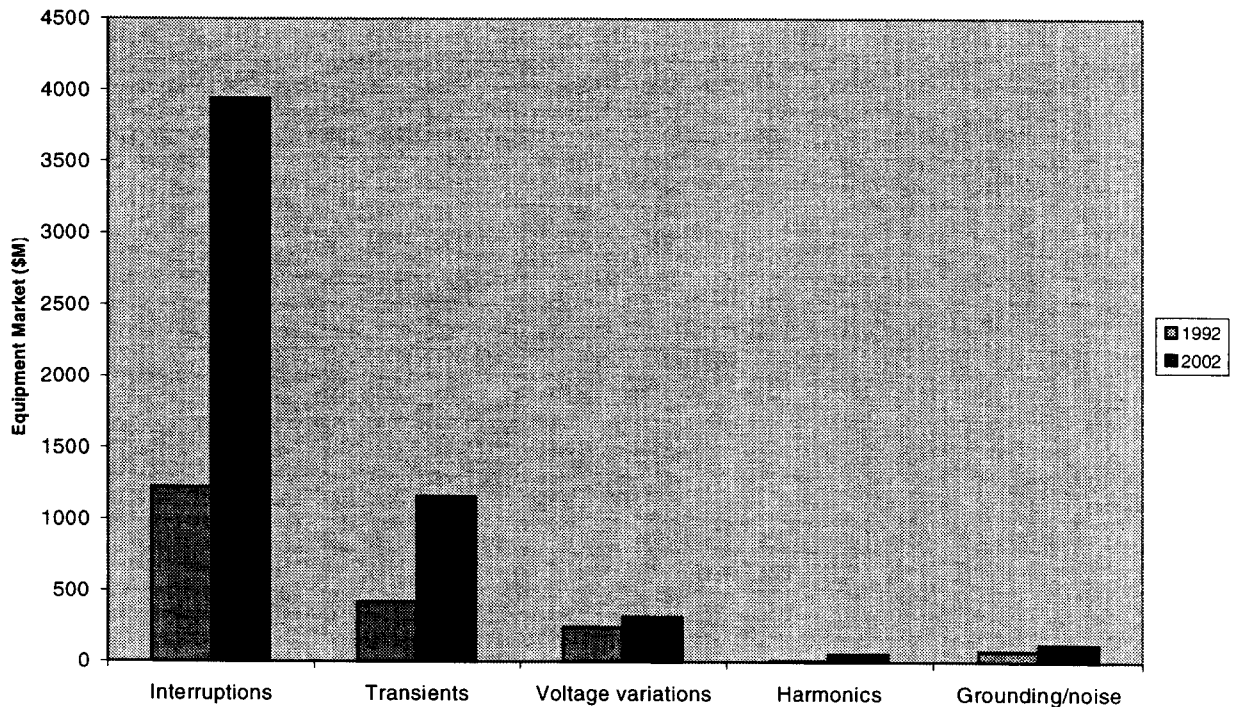
In this case, adding EC capability to the example energy storage systems described in this report will be a very small segment of their impact on the whole field of energy storage technology; just how small is indicated by our projected EC market total. If all applications in Tables 4 and 5 were realized, the annual flywheel market would total \$553 million. However, the cost of the associated ECs, using 5-year costs, would be only \$1.3 million.

**Table 6. Comparison of Near-term and 5-year EC Costs Based on TSI Flywheels**

Example Flywheel Size	Capacitor Size	1-year Cost	5-year Cost <sup>1</sup>
0.5 kWh	2.4 kJ	\$168	\$4
2.5 kWh	6 kJ	\$300	\$5
25 kWh	20 kJ	\$600	\$10
200 kWh	160 kJ	\$4800	\$80

1. Assumes implementation of ESMA technology resulting in costs 50¢-\$1.50/kJ.

Figure 3 shows the scale of the overall market that these systems target. As shown, the total value of the U.S. market for power quality equipment in 1992 was \$1977 million. This market is projected to grow to \$5 to \$6 billion in 2002.



**Figure 3. U.S. power quality equipment market segments.\***

\*Source: EPRI Distribution Power Quality Report (#RP3098-01)

Consequently, the flywheel/EC systems described constitute 10-15% of the power quality equipment market as it exists today. The true market would be substantially larger, as it includes remote power (approximately \$1 billion in the PV market alone) and other segments not considered in the data represented by Figure 3.

## **6. Conclusions**

### **6.1. Flywheel Status**

The representative TSI flywheel used in this study is presently in the prototype test stage as a direct replacement for a storage battery in a communications application, and should also be tested as the primary storage medium in a demonstration PV system. TSI and Solarex are proceeding independently with a preliminary investigation of the interaction of PV modules and the TSI flywheel.

### **6.2. Development of Low-cost ECs**

The Russian firm ESMA has substantial experience in designing and operating ECs in a number of applications, including demonstration projects with the U.S. Army, the National Aeronautics and Space Administration (NASA), and EPRI. Of particular interest is the use of ECs as the sole energy storage medium for various vehicles, which required the development of ECs with characteristics very different from traditional capacitor applications, but very close to those which could replace lead-acid batteries in PV applications and other applications. ESMA's projected prices are drastically lower than current capacitor prices. This issue should be addressed with respect to broad use in energy systems, including PV systems.

### **6.3. Flywheel/Capacitor Synergy**

The primary hypothesis this study—that a synergistic relationship exists between flywheels and ECs in energy storage/delivery systems—has been confirmed conceptually. Further investigation is needed to quantify the performance and economic tradeoffs of this synergy and its effect on overall system costs.

Specifically, effort should be directed at determining whether adding a large EC to a flywheel would, by insulating the flywheel from demand surges:

- enable major changes in flywheel design (lighter shaft, smaller conductor, etc.);
- enable reduction in nominal flywheel capacity for a given application;
- lengthen system life; and/or
- significantly decrease the overall storage system's cost.

Intentionally left blank.

## **7. Appendix A: Capacitor Manufacturers and Technologies**

### **Alupower**

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. Their capacitor has an RC time constant of 2.5 s. The form factor is prismatic. Operating voltage is set at 3.0 V maximum. Alupower has pilot line equipment in place.

### **Asahi**

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. The form factor is a cylinder. They have product lines of low-voltage ECs in sizes up to 50 F, sold mainly for memory backup and related applications. Asahi Glass has presented several papers describing development activities of large, high-power capacitors.

### **Cap-XX**

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. Cap-XX has an operating pilot production line and anticipates that costs will decrease as production volume increases.

### **ECOND International, Inc.**

The technology is a double-layer capacitor based on carbon electrodes and an aqueous electrolyte. Their form factor is a right cylinder. ECOND has been manufacturing large, high-voltage capacitors for more than 10 years, and has many thousands of units in use in various military and automotive applications in Russia, and more recently in the U.S. They recently supplied 1.6 MJ of 200-V capacitors to NASA for a hybrid bus project. These units were rated at 50 kJ each. ECOND presently manufactures their product in Moscow.

### **ELIT Stock Co.**

ELIT has two technologies: a symmetric carbon system and a carbon/metal-oxide pseudocapacitor with an aqueous electrolyte. Their system has an RC time constant of 0.25 s, and a prismatic form factor. They have been manufacturing large, high-voltage capacitors for more than 7 years, and have many thousands of units in the field in various Russian military and automotive applications. ELIT presently manufactures their product in Kursk, Russia.

### **ESMA Joint Stock Co.**

The technology is a combination of double-layer capacitors based on carbon electrodes with an aqueous electrolyte, and metal-oxide pseudocapacitors using an aqueous electrolyte. Starting capacitors have an RC time constant of approximately 1.0 s and a prismatic form factor. Their traction capacitors have an RC time constant of approximately 12 minutes. They have been manufacturing large, high-voltage capacitors for more than 5 years, and have many units in the field, including several vehicles powered by their traction capacitors.

**Evans Capacitor Co.**

The technology uses an electrolytic capacitor anode (aluminum oxide on aluminum) combined with an electrochemical cathode. This approach circumvents potential voltage imbalance problems associated with multicell components. The component has an RC-time constant of less than 0.5 s, and a right cylinder form factor. Evans is presently fabricating laboratory prototypes.

**Federal Fabrics**

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. They have presented papers describing the performance of their small devices.

**GE**

The technology is a double-layer capacitor based on carbon electrodes with a non-aqueous electrolyte. The form factor is unspecified. Operating voltage is set at 2.5 V maximum. GE has been under contract to Ford Motor Co.

**Maxwell Technologies**

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. The capacitor has an RC time constant of 1.4 s, and the form factor is nearly prismatic. Maxwell has a pilot production line in place. They have assembled large banks of capacitors for UPS applications, and understand how to maintain voltage balance in high-voltage systems.

**NEC Corporation**

The technology is a double-layer capacitor based on carbon electrodes and an aqueous electrolyte. Their main product lines are low-voltage (5.5 V) ECs for memory backup and related applications. NEC has presented papers on development of large capacitors over the past 5 years.

**Panasonic Industrial Co.**

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. The capacitor has an RC time constant of 1.5 s, and a right-cylinder form factor. Panasonic has a pilot production line in place and has been sampling this product (470-F to 1500-F capacitor rated at 2.3 V) for more than 3 years.

**Polystor Corp.**

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. Papers have been presented on small (AA-size) single-cell devices.

**REDOX, Inc.**

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. The capacitor has an RC time constant of 7.0 s. The form factor is prismatic. Redox presently assembles laboratory prototypes, and has constructed several 45-cell modules.

**SAFT**

The technology is a double-layer capacitor based on carbon electrodes with an organic electrolyte. They have reported on cylindrical devices for use in applications ranging from wireless communication to UPS systems.

**SRI**

The energy storage component is based on lithium-ion battery technology. It has been described as a very-high-rate battery having a sloping discharge, like a capacitor. The electrolyte was said to be nonflammable. The RC time constant and the form factor of the technology was not provided. Cycle efficiency is unknown, as is state-of-charge power performance behavior. SRI is developing a pilot line for their product. It is not clear that they have investigated voltage balance in the high-voltage configuration.

Intentionally left blank.

## 8. Appendix B: Vendor Information

Alupower, Inc.  
Alex Karpinski  
82 Mechanic Street  
Pawcatuck, CT 06379  
860-599-1100, ext. 320

Asahi Glass Co. Ltd.  
Takeshi Morimoto  
Research Center  
Japan

Cap-XX Pty. Ltd.  
Dr. George Paul  
Christina Road (cnr Birmingham Ave.)  
Villawood, NSW 2163  
Australia  
612-9914-3703

ECOND International, Inc.  
Frank Lev  
9337-B Katy Freeway  
Houston, TX 77024  
905-479-3202

ELIT Stock Co.  
Alexey Beliakov  
Accumulator plant  
305013, Kursk, Russia  
7-07122-461-51

Evans Capacitor Co.  
David A. Evans  
33 Eastern Ave.  
East Providence, RI 02914  
401-434-5600

Federal Fabrics  
Z. Horiwitz  
15 Middlesex St.  
North Chelmsford, MA 01810  
508-470-1859

GE  
Elihu C. Jerabek  
Corporate Research and Development  
Niskayuna, NY 12309  
518-387-5065

Maxwell Technologies  
Mark S. Cohn  
4949 Greencraig Lane  
San Diego, CA 92123  
619-576-7704

NEC Corporation  
Yoshihiko Saiki  
Circuit Component Division  
Japan

Panasonic Industrial Co.  
Dan Yamashita  
6550 Katella Ave., #17A-11  
Cypress, CA 90630  
714-373-7336

Polystor, Corp.  
James Kaschmitter  
6918 Sierra Ct.  
Dublin, CA 94568  
510-829-6251

REDOX, Inc.  
Nikola Marincic  
24 River Street  
Winchester, MA 01890  
617-729-3179

SAFT America, Inc.  
Guy Chagnon  
107 Beaver Court,  
Cockeysville, MD 21030  
410-771-3200

SRI International  
Philip Cox  
33 Ravenwood Ave.  
Menlo Park, CA 94025  
415-859-2938

Intentionally left blank.

## 9. Appendix C: Net Present Value Analysis (Example)

Conventional Batteries					Flywheel				Electrochemical Capacitor			
Year	PV Array	Storage	Other BOS	Total	PV Array	Storage	Other BOS	Total	PV Array	Storage	Other BOS	Total
1	6	3	1	10	6	9	0	15	6	45	1	52
2			0.5	0.5			0.1	0.1			0	0
3			0.5	0.5			0.1	0.1			0	0
4			0.5	0.5			0.1	0.1			0	0
5			0.5	0.5			0.5	0.5			0	0
6			0.5	0.5			0.1	0.1			0	0
7		3	0.5	3.5			0.1	0.1			0	0
8			0.5	0.5			0.1	0.1			0	0
9			0.5	0.5			0.1	0.1			0	0
10			1	1			0.5	0.5			1	1
11			0.5	0.5			0.1	0.1			0	0
12			0.5	0.5			0.1	0.1			0	0
13			0.5	0.5			0.1	0.1			0	0
14		3	0.5	3.5			0.1	0.1			0	0
15			0.5	0.5			0.5	0.5			0	0
16			0.5	0.5			0.1	0.1			0	0
17			0.5	0.5			0.1	0.1			0	0
18			0.5	0.5			0.1	0.1			0	0
19			0.5	0.5			0.1	0.1			0	0
20			1	1			0.5	0.5			1	1
21		3	0.5	3.5			0.1	0.1			0	0
22			0.5	0.5			0.1	0.1			0	0
23			0.5	0.5			0.1	0.1			0	0
24			0.5	0.5			0.1	0.1			0	0
25			0.5	0.5			0.5	0.5			0	0
26			0.5	0.5			0.1	0.1			0	0
27			0.5	0.5			0.1	0.1			0	0
28		3	0.5	3.5			0.1	0.1			0	0
29			0.5	0.5			0.1	0.1			0	0
30			1	1			0.5	0.5			1	1
Total				38				20.3				55
Discount Rate	10%											
NPV				18.2				16.6				52.7



## Distribution

Bob Weaver  
777 Wildwood Lane  
Palo Alto, CA 94303

Per Danfors  
ABB Power T&D Co., Inc.  
16250 West Glendale Drive  
New Berlin, WI 53151

Hans Weinerich  
ABB Power T&D Co., Inc.  
1460 Livingston Ave.  
P.O. Box 6005  
North Brunswick, NJ 08902-6005

Jim Balthazar  
Active Power  
11525 Stonehollow Dr.  
Suite 255  
Austin, TX 78758

Robert Wills  
Advanced Energy Systems  
Riverview Mill  
P.O. Box 262  
Wilton, NH 03086

B. Tiedeman  
Alaska State Div. of Energy  
333 West Fourth Ave.  
Suite 220  
Anchorage, AK 99501-2341

Percy Frisbey  
Alaska State Div. of Energy  
333 West Fourth Ave.  
Suite 220  
Anchorage, AK 99501-2341

P. Crump  
Alaska State Div. of Energy  
333 West Fourth Ave.  
Suite 220  
Anchorage, AK 99501-2341

Michael L. Gravely  
American Superconductor Corp.  
8371 Bunchberry Court  
Citrus Heights, CA 95610

C. Shih  
American Elec. Pwr. Serv. Corp.  
1 Riverside Plaza  
Columbus, OH 43215

Christopher G. Strug  
American Superconductor Corp.  
Two Technology Drive  
Westborough, MA 01581

Meera Kohler  
Anchorage Municipal Light & Pwr  
1200 East 1st Avenue  
Anchorage, AK 99501

Tim Ball  
Applied Power Corporation  
Solar Engineering  
1210 Homann Drive SE  
Lacey, WA 98503

Ralph M. Nigro  
Applied Energy Group, Inc.  
46 Winding Hill Drive  
Hockessin, DE 19707

Christian St-Pierre  
ARGO-TECH Productions, Inc.  
Subsidiary of Hydro-Quebec  
1580 de Coulomb  
Boucherville, QC J4B 7Z7  
CANADA

Gary Henriksen  
Argonne National Laboratories  
9700 South Cass Avenue  
CTD, Bldg. 205  
Argonne, IL 60439

Bill DeLuca  
Argonne National Laboratories  
9700 South Cass Avenue  
CTD, Bldg. 205  
Argonne, IL 60439

Herb Hayden  
Arizona Public Service  
400 North Fifth Street  
P.O. Box 53999, MS8931  
Phoenix, AZ 85072-3999

Ray Hobbs  
Arizona Public Service  
400 North Fifth Street  
P.O. Box 5399, MS8931  
Phoenix, AZ 85072-3999

Robert Hammond  
Arizona State University East  
6001 S. Power Rd.  
Bldg. 539  
Mesa, AZ 85206

Edward C. Kern  
Ascension Technology, Inc.  
P.O. Box 6314  
Lincoln, MA 01773-6314

Gary Markle  
AVO International  
510 Township Line Rd.  
Blue Bell, PA 19422

Glenn Campbell  
Babcock & Wilcox  
P.O. Box 785  
Lynchburg, VA 24505

Richard L. Hockney  
Beacon Power Corp.  
6 Gill St.  
Woburn Industrial Park  
Woburn, MA 01801-1721

Michael L. Bergey  
Bergey Windpower  
2001 Priestley Avenue  
Norman, OK 73069

Klaus Kramer  
Berliner Kraft und Licht (BEWAG)  
Stauffenbergstrasse 26  
1000 Berlin 30  
GERMANY

Massoud Assefpour  
BHP Research & Tech Dev.  
600 Bourke Street  
Melbourne Victoria, 3000  
AUSTRALIA

Samuel B. Wright  
Boeing  
Inform., Space & Defense Sys.  
P.O. Box 3999 MS 82-97  
Seattle, WA 98124-2499

Gerald W. Braun  
BP Solarex  
630 Solarex Court  
Frederick, MD 21703

Salim Jabbour  
Business Management Consulting  
24704 Voorhees Drive  
Los Altos Hills, CA 94022

Dr. Sudhan S. Misra  
C&D Charter Pwr. Systems, Inc.  
Washington & Cherry Sts.  
Conshohocken, PA 19428

Dr. Les Holden  
C&D Charter Pwr. Systems, Inc.  
Washington & Cherry Sts.  
Conshohocken, PA 19428

Larry S. Meisner  
C&D Powercom  
1400 Union Meeting Road  
P.O. Box 3053  
Blue Bell, PA 19422-0858

Jon Edwards  
California Energy Commission  
1516 Ninth Street, MS-46  
Sacramento, CA 95814

J. Holmes  
California State Air Resc. Board  
Research Division  
P.O. Box 2815  
Sacramento, CA 95812

Pramod P. Kulkarni  
California Energy Commission  
Research & Dev. Office  
1516 9th Street, MS43  
Sacramento, CA 95814-5512

Rod Boucher  
Calpine Corporation  
50 W. San Fernando  
Suite 550  
San Jose, CA 95113

Tom Lovas  
Chugach Elec. Association, Inc.  
P.O. Box 196300  
Anchorage, AK 99519-6300

John Cooley  
Chugach Elec. Association, Inc.  
P.O. Box 196300  
Anchorage, AK 99519-6300

M. Lebow  
Consolidated Edison  
4 Irving Place  
New York, NY 10003

N. Tai  
Consolidated Edison  
4 Irving Place  
New York, NY 10003

R. Stack  
Corn Belt Electric Cooperative  
P.O. Box 816  
Bloomington, IL 61702

R. B. Sloan  
Crescent EMC  
P.O. Box 1831  
Statesville, NC 28687

J. Michael Hinga  
Delphi Energy & Engine  
Management Systems  
P.O. Box 502650  
Indianapolis, IN 46250

Bob Galyen  
Delphi Energy & Engine  
Management Systems  
P.O. Box 502650  
Indianapolis, IN 46250

Bob Rider  
Delphi Energy & Engine  
Management Systems  
P.O. Box 502650  
Indianapolis, IN 46250

Paul Maupin  
Department of Energy  
19901 Germantown Rd  
ER-14 E-422  
Germantown, MD 20874-1290

Albert R. Landgrebe  
Department of Energy - Retired  
B14 Suffex Lane  
Millsboro, DE 19966

Joseph J. Iannucci  
Distributed Utility Associates  
1062 Concannon Blvd.  
Livermore, CA 94550

Alan Collinson  
EA Technology Limited  
Chester CH1 6ES  
Capenhurst, England  
UNITD KINGDOM

Jim DeGruson  
Eagle-Picher Industries. Inc.  
C & Porter Street  
Joplin, MO 64802

M. Stanton  
East Penn Manufact. Co., Inc.  
Deka Road  
Lyon Station, PA 19536

Daniel R. Bruck  
ECG Consulting Group, Inc.  
55-6 Woodlake Road  
Albany, NY 12203

Steve Eckroad  
Elec. Pwr. Research Institute  
P.O. Box 10412  
Palo Alto, CA 94303-0813

Robert Schainker  
Elec. Pwr. Research Institute  
P.O. Box 10412  
Palo Alto, CA 94303-0813

Steve Chapel  
Elec. Pwr. Research Institute  
P.O. Box 10412  
Palo Alto, CA 94303-0813

Phillip C. Symons  
Electrochemical Engineering  
Consultants, Inc.  
1295 Kelly Park Circle  
Morgan Hill, CA 95037

Dave Feder  
Electrochemical Energy  
Storage Systems, Inc.  
35 Ridgedale Avenue  
Madison, NJ 07940

Michael Dodge  
Electrosource  
P.O. Box 7115  
Loveland, CO 80537

Harald Haegermark  
Elforsk-Swedish Elec Utilities R&D Co  
Elforsk AB  
Stockholm, S-101 53  
Sweden

Eric Rudd  
Eltech Research Corporation  
625 East Street  
Fairport Harbor, OH 44077

Jennifer Schilling  
Energetics  
501 School Street SW  
Suite 500  
Washington, DC 20024

Phil DiPietro  
Energetics  
501 School Street SW  
Suite 500  
Washington, DC 20024

Paula A. Taylor  
Energetics  
7164 Gateway Drive  
Columbia, MD 21046

Mindi J. Farber-DeAnda  
Energetics  
501 School Street SW  
Suite 500  
Washington, DC 20024

Howard Lowitt  
Energetics  
7164 Gateway Drive  
Columbia, MD 21046

Rich Scheer  
Energetics  
501 School Street SW  
Suite 500  
Washington, DC 20024

Laura Johnson  
Energetics, Inc.  
7164 Gateway Drive  
Columbia, MD 21046

Greg J. Ball  
Energy & Env. Economics, Inc.  
353 Sacramento Street  
Suite 1540  
San Francisco, CA 94111

Amber Gray-Fenner  
Energy Communications Consulting  
7204 Marigot Rd. NW  
Albuquerque, NM 87120

Al Pivec  
Energy Systems Consulting  
41 Springbrook Road  
Livingston, NJ 07039

Dale Butler  
EnerTec Pty. Ltd.  
349 Coronation Drive  
PO Box 1139, Milton BC Old 4044  
Auchenflower, Queensland, 4066  
AUSTRALIA

Robert Duval  
EnerVision  
P.O. Box 450789  
Atlanta, GA 31145-0789

David H. DaCosta  
Ergenics, Inc.  
247 Margaret King Avenue  
Ringwood, NJ 07456

Erik Hennig  
EUS GmbH  
MunscheidstraBe 14  
Gelsenkirchen, 45886  
Germany

John Breckenridge  
Exide Electronics  
8609 Six Forks Road  
Raleigh, NC 27615

J. Mills  
Firing Circuits, Inc.  
P.O. Box 2007  
Norwalk, CT 06852-2007

James P. Dunlop  
Florida Solar Energy Center  
1679 Clearlake Road  
Cocoa, FL 32922-5703

Steven J. Durand  
Florida Solar Energy Center  
1679 Clearlake Road  
Cocoa, FL 32922-5703

Steven Kraft  
Frost & Sullivan  
2525 Charleston Road  
Mountain View, CA 94043

Dave Coleman  
Frost & Sullivan  
2525 Charleston Road  
Mountain View, CA 94043

Bob Zrebiec  
GE Industrial & Pwr. Services  
640 Freedom Business Center  
King of Prussia, PA 19046

Nick Miller  
General Electric Company  
1 River Road  
Building 2, Room 605  
Schenectady, NY 12345

Declan Daly  
General Electric Drive Systems  
1501 Roanoke Blvd.  
Salem, VA 24153

Gerry Woolf  
Gerry Woolf Associates  
17 Westmeston Avenue  
Rottingdean, East Sussex, BN2 8AL  
UNITED KINGDOM

Anthony B. LaConti  
Giner, Inc.  
14 Spring Street  
Waltham, MA 02451-4497

George Hunt  
GNB Tech. Ind. Battery Co.  
Woodlake Corporate Park  
829 Parkview Blvd.  
Lombard, IL 60148-3249

Joe Szymborski  
GNB Tech. Ind. Battery Co.  
Woodlake Corporate Park  
829 Parkview Blvd.  
Lombard, IL 60148-3249

Sanjay Deshpande'  
GNB Technologies  
Woodlake Corporate Park  
829 Parkview Blvd.  
Lombard, IL 60148-3249

J. Boehm  
GNB Tech. Ind. Battery Co.  
Woodlake Corporate Park  
829 Parkview Blvd.  
Lombard, IL 60148-3249

Steven Haagensen  
Golden Valley Elec. Assoc., Inc.  
758 Illinois Street  
P.O. Box 71249  
Fairbanks, AK 99701

Ben Norris  
Gridwise Engineering Company  
121 Starlight Place  
Danville, CA 94526

Clyde Nagata  
Hawaii Electric Light Co.  
P.O. Box 1027  
Hilo, HI 96720

George H. Nolin  
HL&P Energy Services  
P.O. Box 4300  
Houston, TX 77210-4300

Carl Parker  
ILZRO  
2525 Meridian Parkway  
P.O. Box 12036  
Research Triangle Park, NC 27709

Patrick Moseley  
ILZRO  
2525 Meridian Parkway  
P.O. Box 12036  
Research Triangle Park, NC 27709

Jerome F. Cole  
ILZRO  
2525 Meridian Parkway  
PO Box 12036  
Research Triangle Park, NC 27709

R. Myers  
Imperial Oil Resources, Ltd.  
3535 Research Rd. NW  
Calgary, Alberta, T2L 2K8  
CANADA

Ken Belfer  
Innovative Power Sources  
1419 Via Jon Jose Road  
Alamo, CA 94507

David Warar (2)  
Intercon Limited  
6865 Lincoln Avenue  
Lincolnwood, IL 60646

A. Kamal Kalafala  
Intermagnetics General Corp.  
450 Old Niskayuna Road  
P.O. Box 461  
Latham, NY 12110-0461

John Neal  
International Business & Tech.  
Services, Inc.  
9220 Tayloes Neck Road  
Nanjemoy, MD 20662

Gerard H. C. M. Thijssen  
KEMA T&D Power  
Utrechtseweg 310  
P.O. Box 9035  
ET, Ernhem, 6800  
The Netherlands

Elton Cairns  
Lawrence Berkeley Nat'l Lab  
University of California  
One Cyclotron Road  
Berkeley, CA 94720

Frank McLarnon  
Lawrence Berkeley National Lab  
University of California  
One Cyclotron Road  
Berkeley, CA 94720

Kim Kinoshita  
Lawrence Berkeley Nat'l Lab  
University of California  
One Cyclotron Road  
Berkeley, CA 94720

J. Ray Smith  
Lawrence Livermore Nat'l Lab  
University of California  
P.O. Box 808, L-641  
Livermore, CA 94551

Susan Marie Schoenung  
Longitude 122 West, Inc.  
1010 Doyle Street  
Suite 10  
Menlo Park, CA 94025

Joseph Morabito  
Lucent Technologies, Inc.  
600 Mountain View Ave.  
P.O. Box 636  
Murray Hill, NJ 07974-0636

Cecilia Y. Mak  
Lucent Technologies  
3000 Skyline Drive  
Room 855  
Mesquite, TX 75149-1802

Stephen R. Connors  
Massachusetts Inst of Tech  
The Energy Laboratory  
Rm E40-465  
Cambridge, MA 02139-4307

Dutch Achenbach  
Metlakatla Power & Light  
P.O. Box 359  
3.5 Mile Airport Road  
Metlakatla, AK 99926

D. Nowack  
Micron Corporation  
158 Orchard Lane  
Winchester, TN 37398

Dr. Christine E. Platt  
Nat'l Institute of Standards & Tech.  
Room A225 Administration Bldg.  
Gaithersburg, MD 20899

Byron Stafford  
Nat'l Renewable Energy Lab  
1617 Cole Boulevard  
Golden, CO 80401-3393

Holly Thomas  
Nat'l Renewable Energy Lab  
1617 Cole Boulevard  
Golden, CO 80401-3393

Richard DeBlasio  
Nat'l Renewable Energy Lab  
1617 Cole Boulevard  
Golden, CO 80401-3393

Jim Green  
Nat'l Renewable Energy Lab  
1617 Cole Boulevard  
Golden, CO 80401-3393

Larry Flowers  
Nat'l Renewable Energy Lab  
1617 Cole Boulevard  
Golden, CO 80401-3393

Susan Hock  
Nat'l Renewable Energy Lab  
1617 Cole Boulevard  
Golden, CO 80401-3393

Anthony Price  
National Power PLC  
Harwell Int'l Business Ctr.  
Harwell, Didcot, OX11 0QA  
London

Steven P. Lindenberg  
National Rural Elec Cooperative Assoc.  
4301 Wilson Blvd.  
SSER9-207  
Arlington, VA 22203-1860

Bill Brooks  
NC Solar Center  
Corner of Gorman & Western  
Box 7401 NCSU  
Raleigh, NC 27695-740

Andrew L. Rosenthal  
New Mexico State University  
Southwest Tech. Dev. Institute  
Box 30001/Dept. 3SOL  
Las Cruces, NM 88003-8001

Bart Chezar  
New York Power Authority  
1633 Broadway  
New York, NY 10019

Gary G. Karn  
Northern States Power Co.  
1518 Chestnut Avenue North  
Minneapolis, MN 55403

Denise Zurn  
Northern States Power Co.  
414 Nicollet Mall  
Minneapolis, MN 55401

Jack Brown  
NPA Technology  
Two University Place  
Suite 700  
Durham, NC 27707

John Stoval  
Oak Ridge National Laboratory  
P.O. Box 2008  
Bldg. 3147, MS-6070  
Oak Ridge, TN 37831-6070

Robert Hawsey  
Oak Ridge National Laboratory  
P.O. Box 2008  
Bldg. 3025, MS-6040  
Oak Ridge, TN 37831-6040

James VanCoevering  
Oak Ridge National Laboratory  
P.O. Box 2008  
Bldg. 3147, MS-6070  
Oak Ridge, TN 37831-6070

Brendan Kirby  
Oak Ridge National Laboratory  
P.O. Box 2008  
Bldg. 3147, MS-6070  
Oak Ridge, TN 37831-6070

Hans Meyer  
Omnion Pwr. Engineering Corp.  
2010 Energy Drive  
P.O. Box 879  
East Troy, WI 53120

Douglas R. Danley  
Orion Energy Corporation  
10087 Tyler Place #5  
Ijamsville, MD 21754

John DeStreese  
Pacific Northwest Nat'l Lab  
Battelle Blvd.  
P.O. Box 999, K5-02  
Richland, WA 99352

Daryl Brown  
Pacific Northwest Nat'l Lab  
Battelle Blvd. MS K8-07  
P.O. Box 999  
Richland, WA 99352

Thomas H. Schucan  
Paul Scherrer Institut  
CH - 5232 Villigen PSI  
Switzerland

Brad Johnson  
PEPCO  
1900 Pennsylvania NW  
Washington, DC 20068

Stan Sostrom  
POWER Engineers, Inc.  
P.O. Box 777  
3870 US Hwy 16  
Newcastle, WY 82701

P. Prabhakara  
Power Technologies, Inc.  
1482 Erie Blvd.  
P.O. Box 1058  
Schenectady, NY 12301

Henry W. Zaininger  
Power Technologies, Inc.  
775 Sunrise Avenue  
Suite 210  
Roseville, CA 95661

Rick Winter  
Powercell Corporation  
101 Main Street  
Suite 9  
Cambridge, MA 02142-1519

Reznor I. Orr  
Powercell Corporation  
101 Main Street  
Suite 9  
Cambridge, MA 02142-1519

Jerry Neal  
Public Service Co. of New Mexico  
Alvarado Square MS-BA52  
Albuquerque, NM 87158

Roger Flynn  
Public Service Co. of New Mexico  
Alvarado Square MS-2838  
Albuquerque, NM 87158

Wenceslao Torres  
Puerto Rico Elec. Pwr. Authority  
G.P.O. Box 4267  
San Juan, PR 00936-426

Norman Lindsay  
Queensland Department of  
Mines and Energy  
G.P.O. Box 194  
Brisbane, 4001  
QLD. AUSTRALIA

J. Thompson  
R&D Associates  
2100 Washington Blvd.  
Arlington, VA 22204-5706

Al Randall  
Raytheon Eng. & Constructors  
700 South Ash Street  
P.O. Box 5888  
Denver, CO 80217

K. Ferris  
RMS Company  
87 Martling Avenue  
Pleasantville, NY 10570

Ole Vigerstol  
SAFT America, Inc.  
711 Industrial Blvd.  
Valdosta, GA 13601

Guy Chagnon  
SAFT Research & Dev. Ctr.  
107 Beaver Court  
Cockeysville, MD 21030

Michael C. Saft  
SAFT Research & Dev. Ctr.  
107 Beaver Court  
Cockeysville, MD 21030

G. E. "Ernie" Palomino  
Salt River Project  
P.O. Box 52025  
MS PAB 357  
Phoenix, AZ 85072-2025

H. Lundstrom  
Salt River Project  
P.O. Box 52025  
MS PAB 357  
Phoenix, AZ 85072-2025

Dr. Charles Feinstein  
Santa Clara University  
Dept. of Dec. & Info. Sciences  
Leavey School of Bus. & Admin.  
Santa Clara, CA 95053

Robert Reeves  
Sentech, Inc.  
9 Eaton Road  
Troy, NY 12180

Kurt Klunder  
Sentech, Inc.  
4733 Bethesda Avenue  
Suite 608  
Bethesda, MD 20814

Rajat K. Sen  
Sentech, Inc.  
4733 Bethesda Avenue  
Suite 608  
Bethesda, MD 20814

Nicole Miller  
Sentech, Inc.  
4733 Bethesda Avenue  
Suite 608  
Bethesda, MD 20814

Clay Aldrich  
Siemens Solar  
4650 Adohr Lane  
P.O. Box 6032  
Camarillo, CA 93011

Deepak Divan  
Soft Switching Technologies  
2224 Evergreen Road  
Suite 6  
Middleton, WI 53562

Scott Sklar  
Solar Energy Ind. Assoc. (SEIA)  
122 C Street NW  
4th Floor  
Washington, DC 20001-2104

Naum Pinsky  
Southern California Edison  
2244 Walnut Grove Ave.  
P.O. Box 800, Room 418  
Rosemead, CA 91770

Bruce R. Rauhe, Jr.  
Southern Company Services, Inc.  
600 North 18th Street  
P.O. Box 2625  
Birmingham, AL 35202-2625

K. Vakhshoorzadeh  
Southern Company Services, Inc.  
600 North 18th Street  
P.O. Box 2625  
Birmingham, AL 35202-2625

Richard N. Schweinberg  
Southern California Edison  
6070 N. Irwindale Avenue  
Suite I  
Irwindale, CA 91702

C. Seitz  
SRI International  
333 Ravenswood Avenue  
Menlo Park, CA 94025

George Zink  
Stored Energy Engineering  
7601 E. 88th Place  
Indianapolis, IN 46256

Bob Bish  
Stored Energy Engineering  
7601 E. 88th Place  
Indianapolis, IN 46256

Jon Hurwitch  
Switch Technologies  
4733 Bethesda Avenue  
Suite 608  
Bethesda, MD 20814

Terri Hensley  
Tampa Electric Company  
P.O. Box 111  
Tampa, FL 33601-0111

Thomas J. Jenkin  
The Brattle Group  
44 Brattle Street  
Cambridge, MA 02138-3736

Haukur Asgeirsson  
The Detroit Edison Company  
2000 2nd Ave.  
435 SB  
Detroit, MI 48226-1279

Charles E. Bakis  
The Pennsylvania State University  
227 Hammond Building  
University Park, PA 16802

Michael Orians  
The Solar Connection  
P.O. Box 1138  
Morro Bay, CA 93443

Tom Anyos  
The Technology Group, Inc.  
63 Linden Avenue  
Atherton, CA 94027-2161

Bill Roppenecker  
Trace Engineering Division  
5916 195th Northeast  
Arlington, WA 98223

Bill Erdman  
Trace Technologies  
6952 Preston Avenue  
Livermore, CA 94550

Michael Behnke  
Trace Technologies  
6952 Preston Ave.  
P.O. Box 5049  
Livermore, CA 94550

Donald A. Bender  
Trinity Flywheel Power  
6724D Preston Avenue  
Livermore, CA 94550

Jim Drizos  
Trojan Battery Company  
12380 Clark Street  
Santa Fe Springs, CA 90670

James Fangue  
TU Electric  
R&D Programs  
P.O. Box 970  
Fort Worth, TX 76101

Paul C. Klimas  
U.S. Agency for Intn'l Development  
Center for Environment  
Washington, DC 20523-3800

Jim Daley  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-12 FORSTL  
Washington, DC 20585

Dan T. Ton  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-11 FORSTL  
Washington, DC 20585

James E. Rannels  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-11 FORSTL  
Washington, DC 20585-0121

Gary A. Buckingham  
U.S. Department of Energy  
Albuquerque Operations Office  
P.O. Box 5400  
Albuquerque, NM 87185

Mark B. Ginsberg  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-90 FORSTL 5E-052  
Washington, DC 20585

Alex O. Bulawka  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-11 FORSTL  
Washington, DC 20585

J. A. Mazer  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-11 FORSTL  
Washington, DC 20585

J. P. Archibald  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-90 FORSTL  
Washington, DC 20585

Richard J. King  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-11 FORSTL, 5H-095  
Washington, DC 20585

Russ Eaton  
U.S. Department of Energy  
Golden Field Office  
1617 Cole Blvd., Bldg. 17  
Golden, CO 80401

Kenneth L. Heitner  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-32 FORSTL  
Washington, DC 20585

Bob Brewer  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-10 FORSTL  
Washington, DC 20585

Neal Rossmeissl  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-13 FORSTL  
Washington, DC 20585

Allan Jelacic  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-12 FORSTL  
Washington, DC 20585

R. Eynon  
U.S. Department of Energy  
1000 Independence Ave. SW  
EI-821 FORSTL  
Washington, DC 20585

Alex G. Crawley  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-90 FORSTL  
Washington, DC 20585

Philip N. Overholt  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-11 FORSTL  
Washington, DC 20585-0121

W. Butler  
U.S. Department of Energy  
1000 Independence Ave. SW  
PA-3 FORSTL  
Washington, DC 20585

Pandit G. Patil  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-32 FORSTL  
Washington, DC 20585

Allan Hoffman  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-10 FORSTL  
Washington, DC 20585

Jack Cadogan  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-11 FORSTL  
Washington, DC 20585

Joe Galdo  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-10 FORSTL  
Washington, DC 20585

Dr. Gerald P. Ceasar  
U.S. Department of Commerce  
NIST/ATP  
Bldg 101, Room 623  
Gaithersburg, MD 20899

Dr. Imre Gyuk  
U.S. Department of Energy  
1000 Independence Ave. SW  
EE-14 FORSTL  
Washington, DC 20585

Steve Bitterly  
U.S. Flywheel Systems  
1125-A Business Center Circle  
Newbury Park, CA 91320

Wayne Taylor  
U.S. Navy  
Code 83B000D, NAWS  
China Lake, CA 93555

Edward Beardsworth  
UFTO  
951 Lincoln Avenue  
Palo Alto, CA 94301-3041

Tien Q. Duong  
United States Department of Energy  
1000 Independence Ave. SW  
EE-32 FORSTL, Rm. 5G-030  
Washington, DC 20585

John Herbst  
University of Texas at Austin  
J.J. Pickel Research Campus  
Mail Code R7000  
Austin, TX 78712

Max Anderson  
University of Missouri - Rolla  
112 Electrical Eng. Bldg.  
Rolla, MO 65401-0249

G. Alan Palin  
Urenco (Capenhurst) Ltd.  
Capenhurst, Chester, CH1 6ER  
UNITED KINGDOM

Steve Hester  
Utility Photo Voltaic Group  
1800 M Street NW  
Washington, DC 20036-5802

Mike Stern  
Utility Power Group  
9410-G DeSoto Avenue  
Chatsworth, CA 91311-4947

Rick Ubaldi  
VEDCO Energy  
12 Agatha Lane  
Wayne, NJ 07470

Gary Verno  
Virginia Power  
Innsbrook Technical Center  
5000 Dominion Blvd.  
Glen Allen, VA 23233

Alex Q. Huang  
Virginia Polytechnic Instit. & State Uni  
Virginia Power Electronics Center  
672 Whittemore Hall  
Blacksburg, VA 24061

Randy Bevin  
Walt Disney World  
Design and Eng'g  
P.O. Box 10,000  
Lake Buena Vista, FL 32830-1000

Gerald J. Keane  
Westinghouse Elec. Corp.  
Energy Management Division  
4400 Alafaya Trail  
Orlando, FL 32826-2399

Howard Saunders  
Westinghouse STC  
1310 Beulah Road  
Pittsburgh, PA 15235

Tom Matty  
Westinghouse  
P.O. Box 17230  
Maryland, MD 21023

Frank Tarantino  
Yuasa, Inc.  
2366 Bernville Road  
P.O. Box 14145  
Reading, PA 19612-4145

Nicholas J. Magnani  
Yuasa, Inc.  
2366 Bernville Road  
P.O. Box 14145  
Reading, PA 19612-4145

Gene Cook  
Yuasa, Inc.  
2366 Bernville Road  
P.O. Box 14145  
Reading, PA 19612-4145

R. Kristiansen  
Yuasa-Exide, Inc.  
35 Loch Lomond Lane  
Middleton, NY 10941-1421

Robert J. Parry  
ZBB Technologies  
11607 West Dearbourn Ave.  
Wauwatosa, WI 53226-3961

Phillip A. Eidler  
ZBB Technologies, Inc.  
11607 West Dearbourn Ave.  
Wauwatosa, WI 53226-3961

MS-0619, Review & Approval For DOE/OSTI (00111) (1)  
MS-0212, Andrew Phillips (10230)  
MS-0340, Jeff W. Braithwaite (1832)  
MS-0457, Gary N. Beeler (2000)  
MS-0537, Stan Atcitty (2314)  
MS-0953, William E. Alzheimer (2500)  
MS-0953, J. Thomas Cutchen (2500)  
MS-0613, Daniel H. Doughty (2521)  
MS-0613, Terry Unkelhaeuser (2521)  
MS-0613, Rudy G. Jungst (2521)  
MS-0614, Dennis E. Mitchell (2522)  
MS-0614, Robert W. Bickes (2523)  
MS-0613, Garth P. Corey (2525)  
MS-0613, Gus P. Rodriguez (2525)  
MS-0613, Terry Crow (2525)  
MS-0613, Imelda Francis (2525)  
MS-0613, Nancy H. Clark (2525)  
MS-0613, Paul C. Butler (2525) (10)  
MS-0613, John D. Boyes (2525)  
MS-0899, Technical Library (4916) (2)  
MS-0741, Sam Varnado (6200)  
MS-0704, Abbas A. Akhil (6201)  
MS-0708, Henry M. Dodd (6214)  
MS-0753, Christopher Cameron (6218)  
MS-0753, Russell H. Bonn (6218)  
MS-0753, Tom Hund (6218)  
MS-0753, John W. Stevens (6218)  
MS-0753, Ward I. Bower (6218)  
MS-0455, Marjorie L. Tatro (6231)  
MS-9403, Jim Wang (8713)  
MS-9018, Central Technical Files (8940-2)  
MS-1193, Dean C. Rovang (9531)